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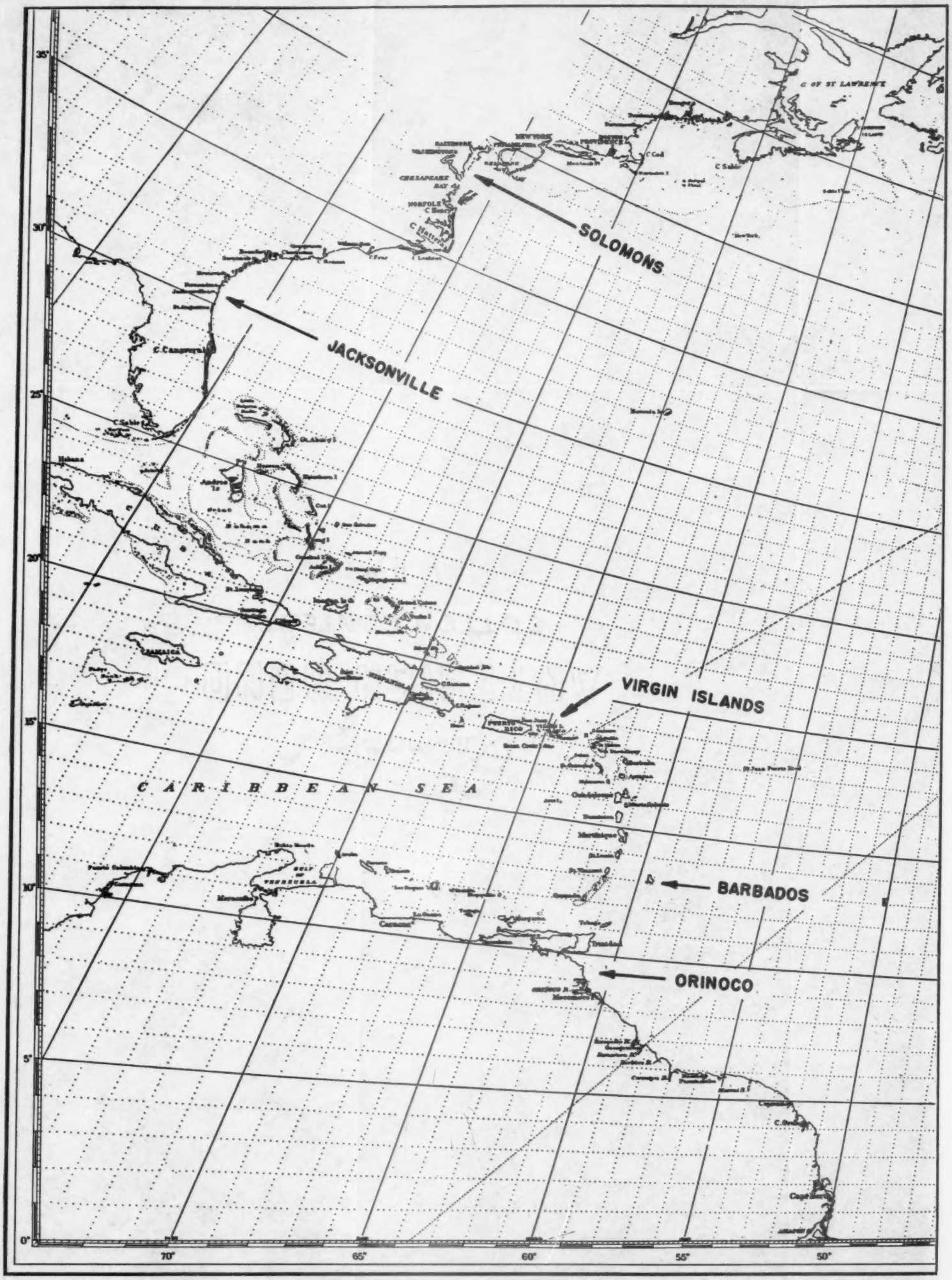

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 909-934, 12 PLS., 15 FIGS. OCTOBER 1946

RECENT RESULTS IN SUBMARINE GEOPHYSICS

BY MAURICE EWING, G. P. WOOLLARD, A. C. VINE, AND J. L. WORZEL

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ABSTRACT

During the war period nearly all the established methods of studying submarine geology were found to have military application, and, as a result of the impetus given to such work by government research and development contracts, new techniques were developed. Thus the field work of the war period has added considerably to knowledge gained through established methods and has demonstrated the potential usefulness to submarine geology of entirely new instrumentation.

The co-operation of geophysicists, submarine geologists, and oceanographers with the Navy's research program has been particularly close and effective. It has led to improvements in the methods of both deep-sea and shallow-water seismic surveys, to advances in the techniques of underwater photography, and to the developments of other rapid systems for collecting information about the sediments. Some examples of the results achieved by investigators at the Woods Hole Oceanographic Institution are presented.

As an example of an entirely new tool for the exploration of ocean basins, a method of acoustically scanning the floor of the deep ocean is explained. This method is particularly promising for the location of active submarine volcanoes and isolated submerged sea mounts which cannot be easily found by conventional sounding techniques.

INTRODUCTION

The present report covers investigations of submarine geology made by the authors during the years 1938–1945. The deep submarine seismic investigations started in 1937 were interrupted by war work at a point when they seemed about to produce results. Prior to the war, under-water photography had progressed suc-

cessfully, and over 150 photographs had been taken. Some military applications of under-water photography were developed during the war. Included here with the earlier results are some geological results and instruments which resulted as by-products of the war activities. Most of the war work was done in connection with war contracts between the Woods Hole Oceanographic Institution, the Navy, and Section 6.1 of the National Defense Research Committee.

ACKNOWLEDGMENTS

Seismic refraction measurements in shallow water were supported by the Bureau of Ordnance and the Bureau of Ships, Navy Department, through contracts with the Woods Hole Oceanographic Institution. B. L. Snavely, J. E. Owen, Gale White, J. L. Worzel, and Maurice Ewing are primarily responsible for the geophysical work, which was done on board vessels of the U. S. Navy. G. P. Woollard produced the geological sections, and A. P. Crary contributed greatly to the bubble-pulse investigation in 1941.

Seismic refraction measurements in deep water were supported by The Geological Society of America and the Woods Hole Oceanographic Institution. Most of the work was done on board the ketch ATLANTIS of the Woods Hole Oceanographic Institution, although some development work was done on the ketch CULVER of the Royal Society. Part of the work was aided by the facilities of the Bermuda Biological Station and Lehigh University. A. C. Vine, J. L. Worzel, G. P. Woollard, and Maurice Ewing are primarily responsible for the technical work.

Eleuthera Island bathymetry was done on board the U.S.C.G.R. VALOR under the supervision of Marshall Schalk.

Work on a new method of sampling the ocean bottom was supported by Section 6.1 of the National Defense Research Committee through a contract with the Woods Hole Oceanographic Institution. J. L. Worzel, A. C. Vine, and Maurice Ewing are primarily responsible for the technical work.

Photography of the ocean bottom was supported originally by the National Geographic Society and the Woods Hole Oceanographic Institution. War-time modifications were supported by Section 6.1 of the National Defense Research Committee through contracts with the Woods Hole Oceanographic Institution. A. C. Vine, J. L. Worzel, and Maurice Ewing are responsible for the technical work.

Work on long-range sound transmission in the ocean was supported by Section 6.1 of the National Defense Research Committee and later by the Bureau of Ships, Navy Department, through contracts with the Woods Hole Oceanographic Institution. J. L. Worzel, R. J. McCurdy, J. A. Peoples, Jr., N. C. Steenland, E. L. Newhouse III, D. T. Parsons, W. S. von Arx, and Maurice Ewing are primarily responsible for the technical work.

SEISMIC REFRACTION MEASUREMENTS IN SHALLOW WATER

GENERAL STATEMENT

Incidental to work done jointly by the Woods Hole Oceanographic Institution and the Navy Department, seismic refraction data were obtained in coastal waters in

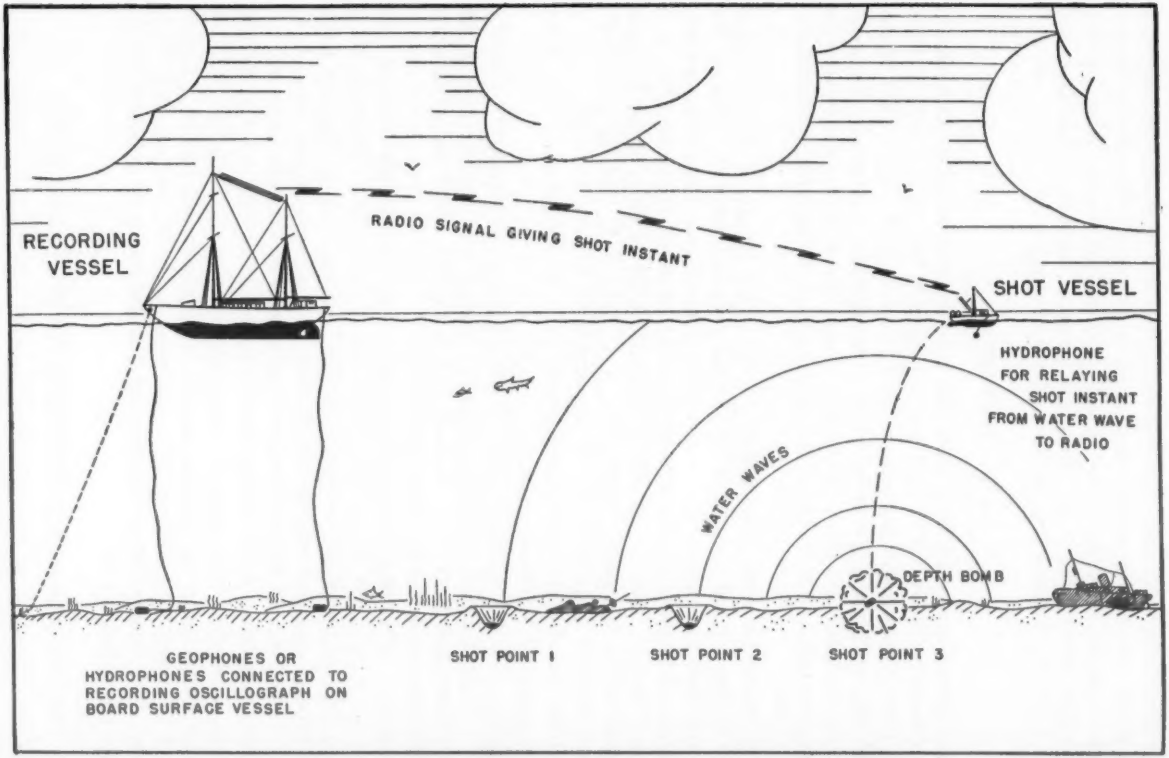

RECORDING VESSEL
RADIO SIGNAL GIVING SHOT INSTANT
SHOT VESSEL
HYDROPHONE FOR RELAYING SHOT INSTANT FROM WATER WAVE TO RADIO
WATER WAVES
DEPTH BOMB
GEOPHONES OR HYDROPHONES CONNECTED TO RECORDING OSCILLOGRAPH ON BOARD SURFACE VESSEL
SHOT POINT 1
SHOT POINT 2
SHOT POINT 3

FIGURE 1.—*General arrangement for shallow-water seismic measurements*
depth less than 600.

FIGURE 1.—*General arrangement for shallow-water seismic measurements*
depth less than 600.

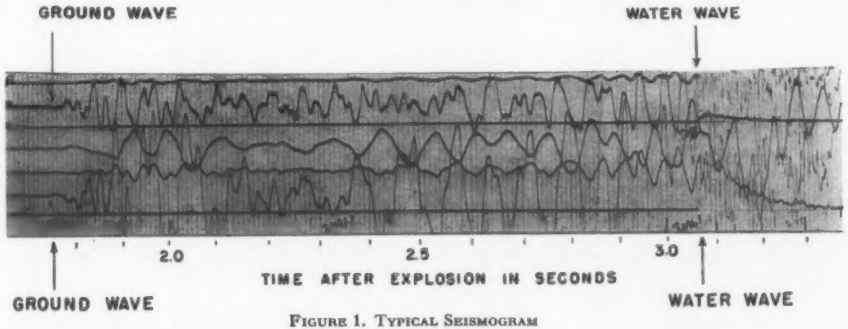


FIGURE 1. TYPICAL SEISMOGRAM

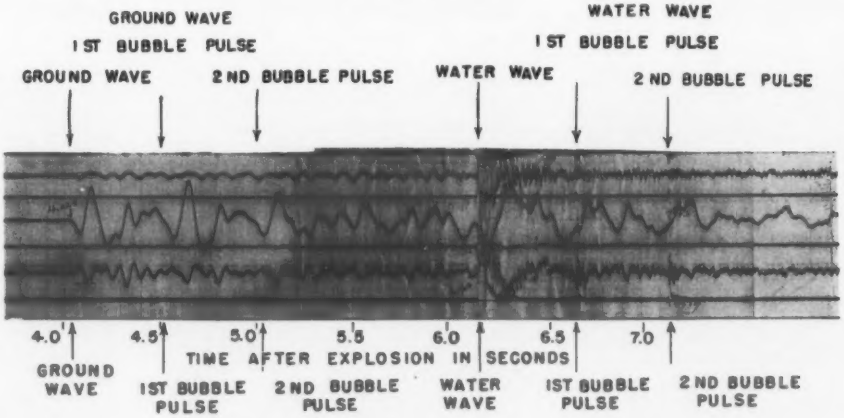


FIGURE 2. SEISMOGRAM SHOWING EFFECT OF BUBBLE PULSES

TYPICAL SHALLOW-WATER SEISMOGRAMS

FIGURE 1. .0000 SEC.

FIGURE 4. .0043 SEC.

FIGURE 2. .0014 SEC.

FIGURE 5. .0098 SEC.

FIGURE 3. .0028 SEC.

FIGURE 6. .0168 SEC.

OSCILLATING GAS BUBBLE FROM DETONATOR EXPLODED UNDER WATER

depths of 10 and 20 fathoms. These data extend to new areas our earlier seismic work in the submerged Atlantic Coastal Plain (Ewing, Crary, and Rutherford, 1937). Measurements were made in Chesapeake Bay, off Jacksonville, Florida, off St. Thomas, Virgin Islands, off Barbados, and on the Orinoco Delta. These stations are shown in Plate 1.

A total of 446 shots were fired, ranging from half a pound to 300 pounds of TNT. Of these, half were on bottom, and half were at mid-depth. Distances between shot and recording positions ranged from a few hundred feet up to 27 miles and were determined by measuring the travel time of the water wave. The shot instant was transmitted to the recording vessel by radio. All recording was done with an oscillograph on board the USS SALUDA, using two hydrophones and one geophone, all placed close together on bottom. The hydrophones and the geophone gave similar records. The general arrangement is shown in Figure 1.

Figure 1 of Plate 2 is a typical record which shows a series of low-frequency ground waves followed by a water wave of characteristically higher frequency. The time marks are at intervals of 1/100 second. The multiple traces correspond to different frequency bands—in some cases from different acoustical pickups and in others from different filters applied to the output of a single pickup.

BUBBLE PULSES FROM UNDER-WATER EXPLOSIONS

Historical background.—A phenomenon first reported by Blochmann (1898) but not widely known by geophysicists is of importance in all under-water work with explosives. He noted that a single under-water explosion produced two or more definite pressure waves as though there were several separate explosions each less intense than the preceding. His explanation was that the gas bubble formed by the products of the explosion expands to a size so large that the pressure of the gas is below that of the surrounding water. The bubble then contracts sufficiently to produce a very high pressure and emit a new sound wave.

Evidence obtained in 1941.—While working on another problem in 1941, we encountered multiple sounds from single explosions. Unaware of Blochmann's work, we arranged for H. E. Edgerton to take high-speed motion pictures of detonators fired under about 3 feet of water. These pictures (*see* Pls. 3 and 4) show that the gas bubble definitely oscillates. The radius of the oscillating gas bubble as a function of time, determined from these photographs, is shown in Figure 2. Oscillograms made at the time these pictures were taken showed that a sound pulse was emitted each time the bubble reached minimum radius.

The next stage of the investigation was a very rough determination of time interval for the first bubble oscillation as a function of depth and charge size. This led to the empirical equation:

$$T = 12.5\, W^{1/3}\,(h + 33)^{-1} \qquad (1)$$

when W is the weight of TNT in pounds, h is the depth of the charge in feet, and T is the time interval in seconds. Usually three or four impulses were recorded from each explosion, with decreasing time intervals and intensities for successive pulses.

More recent work by several investigators, and extension of the data to greater depths, have shown this equation to be in error. The corrected equation is:

$$T = 4.19\, W^{1/3}\, (h + 33)^{-5/6} \qquad (2)$$

Evidence from refraction seismograms.—Most of our refraction seismograms show evidence of this phenomenon. For example, the seismogram shown in Figure 2 of

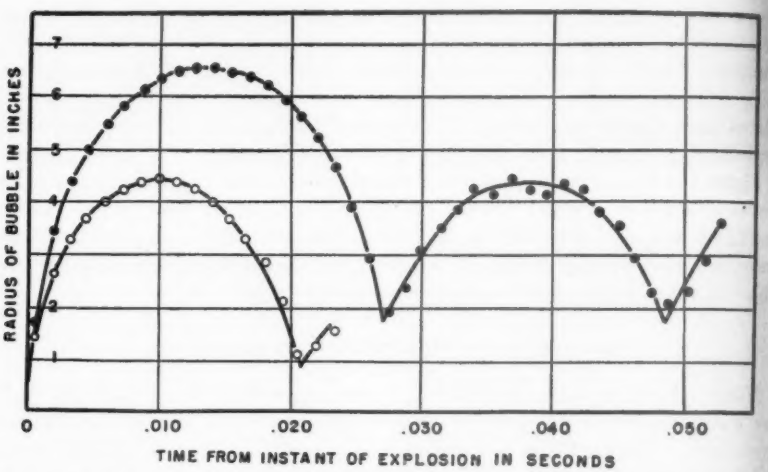


FIGURE 2.—*Variation of size of spherical explosion bubble with time, from instant of explosion* ○—Lead azide detonator. ●—#6 tetro detonator. Taken from high speed motion pictures—744 pictures/sec. Sound impulse starts at each minimum.

Plate 2 has three successive water-wave signals. On this record there are also three ground-wave signals which have the same time intervals between themselves as the water waves. This proves that there were in effect three explosions at intervals of roughly half a second, each of which gave a complete set of ground and water waves. Figure 3 is a plot of the first bubble-pulse intervals for all shots. The curves in this figure are drawn from equation (2) and are in good agreement with the observations.

Practical importance.—At least one bubble-pulse sound emission was observed on 63 per cent of all our bottom shots and on 87 per cent of the mid-depth shots. The great majority of the mid-depth shots showed two or three bubble pulses. Obviously the successive sound emissions from the oscillating gas bubble can produce serious interference in seismic prospecting of water-covered areas, particularly in reflection work.

The multiple sound emissions from explosions in water-filled quarries, for which no explanation could be found when they were observed some 10 years ago, are now explained. (*See* records 69–70–6 and 69–71–4, Leet and Ewing, 1932, p. 165.)

As pointed out recently by Lay (1945), the multiple sound emission may be eliminated by placing the charge near enough to the water surface so that it blows out on

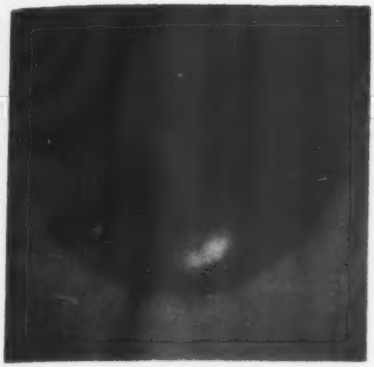


FIGURE 1. .0238 SEC.

FIGURE 4. .0420 SEC.

FIGURE 2. .0308 SEC.

FIGURE 5. .0476 SEC.

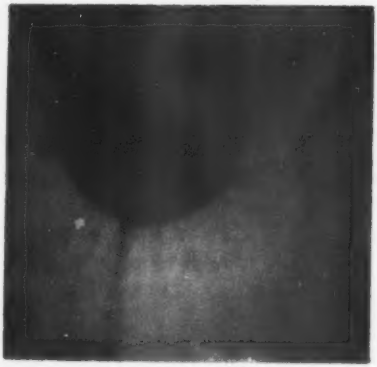


FIGURE 3. .0364 SEC.

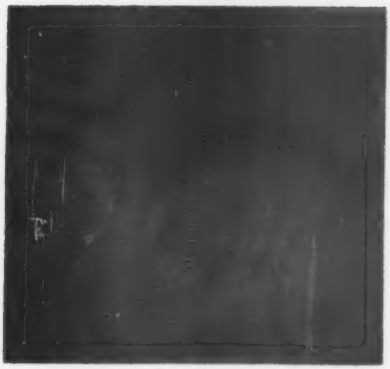


FIGURE 6. .0532 SEC.

OSCILLATING GAS BUBBLE FROM DETONATOR EXPLODED UNDER WATER

SEISMOGRAM SHOWING DISPERSION IN WATER WAVE

Dispersion in Water Wave in Shot No. 91 at Jacksonville Shoal

Depth of Water = 60 feet, Charge Weight = 5 lbs.; Charge and Hydrophone beached on bottom.

the first expansion of the bubble. A curve showing the critical depth for bubble pulses as a function of weight of TNT, which has been compiled from various sources, appears in Figure 4.

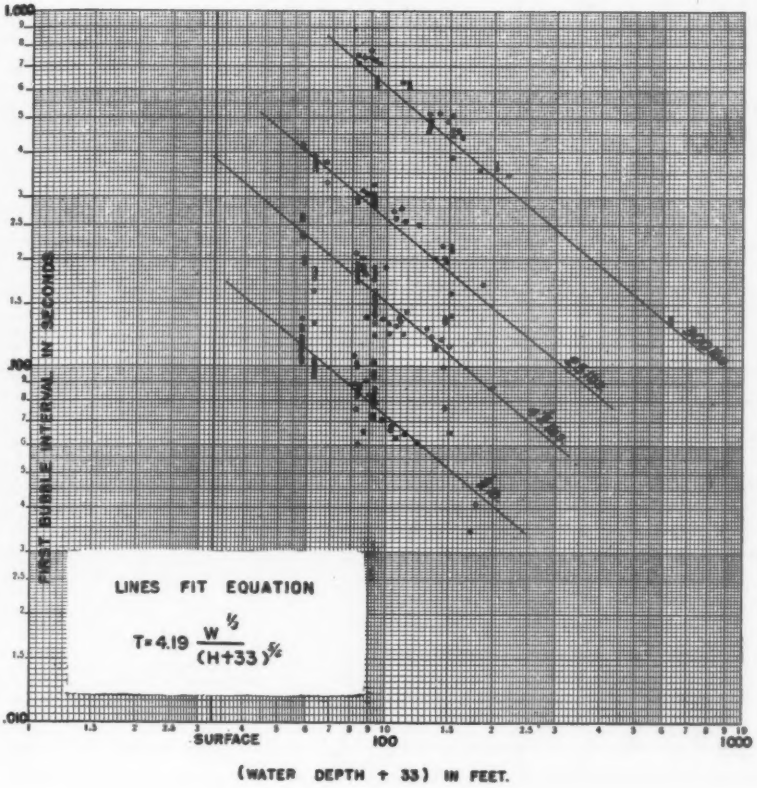


FIGURE 3.—*First bubble pulse interval*

DISPERSION IN THE WATER WAVE

General statement.—Dispersion in the water wave, with the higher-frequency sound arriving ahead of the lower, was observed at all stations. Although this phenomenon was observed by Ewing as early as 1927 in the course of seismic prospecting operations in the coastal lakes of Louisiana, the present work offered the first opportunity to obtain adequate data for its study.

Plate 5 shows the water-wave portion of a typical seismogram from the Jacksonville Shoal station. The water depth was 60 feet, and the charge was 5 pounds of TNT which was fired on bottom at a distance of about 5 miles. The approximate

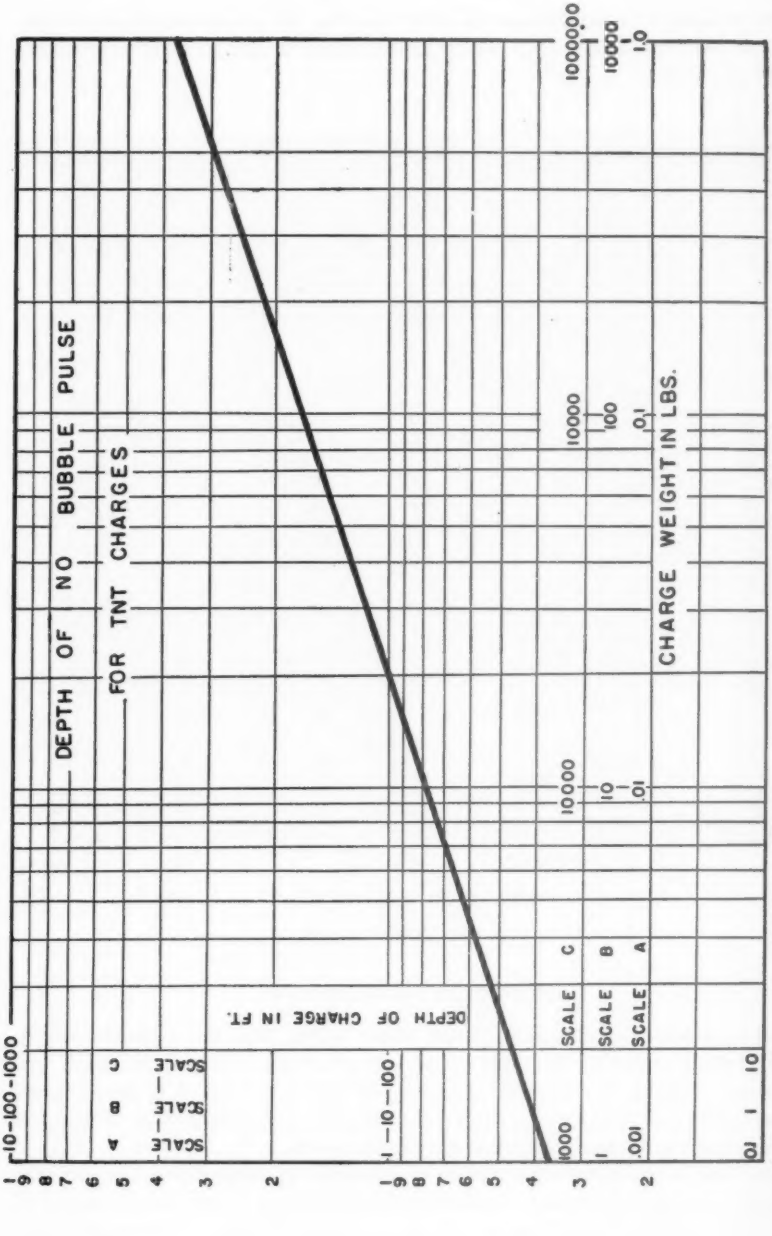


FIGURE 4.—*Critical depth for bubble pulses for TNT charges*

time in seconds, measured from the instant of the explosion, is marked across the top of the record. The water wave from the explosion is a train of waves starting at about 5.55 seconds, and that from the bubble pulse is a similar but weaker train

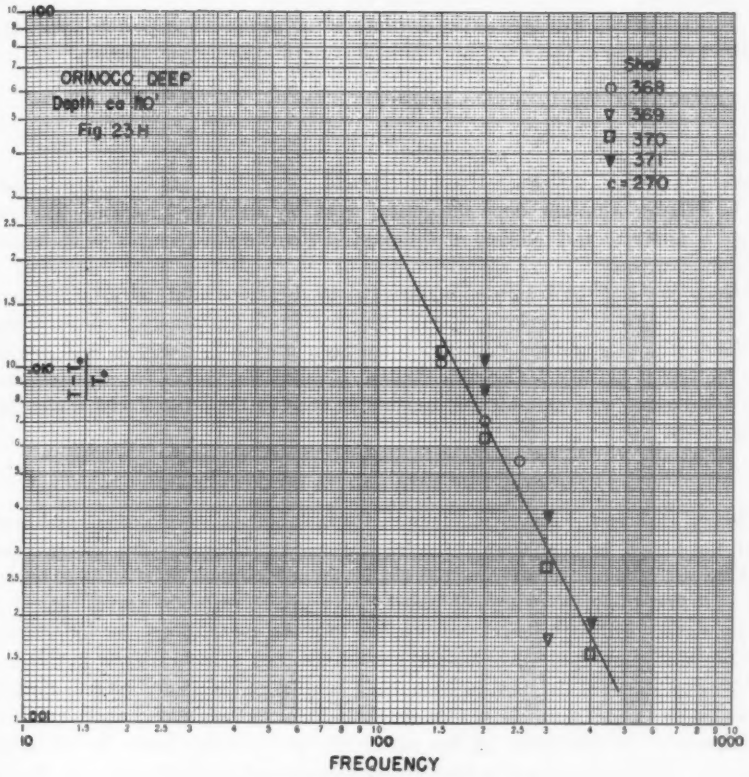


FIGURE 5.—*Typical dispersion curve*

starting at about 5.75 seconds. Traces 3 and 6 in Plate 5 show that the sound velocity varies by about 3 per cent for the frequency range from 500 to 60 cycles per second. It is generally recognized that no velocity variation of this magnitude occurs in water, and our own measurements in deep water have never shown dispersion. Hence, it is clear that the observed dispersion is related to the shallow water. This effect occurs only when the wave length of the sound approaches the water depth. Under these conditions ray acoustics do not hold, and wave acoustics must be used. By using the arrival time of the highest-frequency sound, the normal velocity of sound in sea water can be used for computing distance.

Analysis of the data.—The method of analyzing this dispersion was to select about four seismograms at different distances at each station. In each of these, four

FIGURE 4.—*Critical depth for bubble pulses for TNT charges*

places were selected where the travel time, T, and the frequency, F, of the water waves could be read. A plot of $\log \frac{T - T_o}{T_o}$ against $\log F$ was made for each station where T_o is the travel time for the highest-frequency sound received. Figure 5 is a typical plot. It should be noted that the ordinate $(T - T_o)/T_o$ is identical with $(V_o - V)/V$ which is defined as the dispersion. All of the curves plotted as described above had slopes of the order of -2, indicating the dispersion formula

$$V = V_0 (1 - \frac{C}{F^2}) \tag{3}$$

where C was a constant for each station.

Analysis by C. L. Pekeris.—These results and the original data were turned over to C. L. Pekeris, who had done theoretical work on a similar problem. He established a complete and detailed explanation of the observed dispersion in terms of bottom structure.[1]

Measurement of the dispersion in the water wave may be interpreted by this theory to determine the sound velocity in the ocean bottom to a depth approximately equal to the depth of the water. Although it has been used to date only in shallow water, the method is feasible for oceanic depths. Preliminary plans for observations in the deep ocean, with suitable instruments to observe these interfacial waves, have been made.

TRAVEL-TIME DATA AND ITS INTERPRETATION

General statement.—Travel-time graphs for each station were plotted, and depths were calculated by the standard refraction-seismic methods (*see* Ewing, Crary, Rutherford, 1937). One of these plots is shown in Figure 6. The distance between the shot and the receiver was obtained in every case from the travel time of the water wave. Although it was not possible to shoot reversed profiles for obtaining the slopes of the strata, this omission should not lead to serious error in the depth determination, since the profiles were made parallel to the shore line and along the probable strike. Figure 7 shows the depth to basement calculated at each station.

Solomons.—At Solomons, off the mouth of the Patuxent River in Chesapeake Bay, the depth to basement at the shoal seismic station was 3050 feet. At the deep seismic station about 4 miles to the east, the depth to basement was 2950 feet. The probable depths based on geologic evidence were 2800 feet and 3100 feet respectively. These were determined on the assumption of a constant slope from the Fall Line near Quantico, Virginia, 40 miles to the westward, to the Ohio Oil Company's L. G. Hammon, No. 1 well near Salisbury, Maryland (Richards, 1945), 50 miles to the east.

Jacksonville.—The seismic determinations of the depths to basement were 6250 feet at the shoal station and 7600 feet at the deep station. As there were no well data in the immediate vicinity, the basement slope indicated by these determinations was used to project the basement surface from the nearest well, St. Mary's River Oil Corporation, Hilliard Turpentine Company No. 1, about 45 miles to the

[1] Submitted for publication to The Geological Society of America

northwest, near Hilliard, Florida, to these stations. The projected depths were 5900 feet for the shoal station and 7200 feet for the deep station.

Virgin Islands.—The Virgin Island Shoal station starts a few hundred yards south of Water Island and runs about E. 10° S. for a distance of about 10 miles to a depth of about 1300 feet. The velocity is about 13,160 ft./sec. The underlying

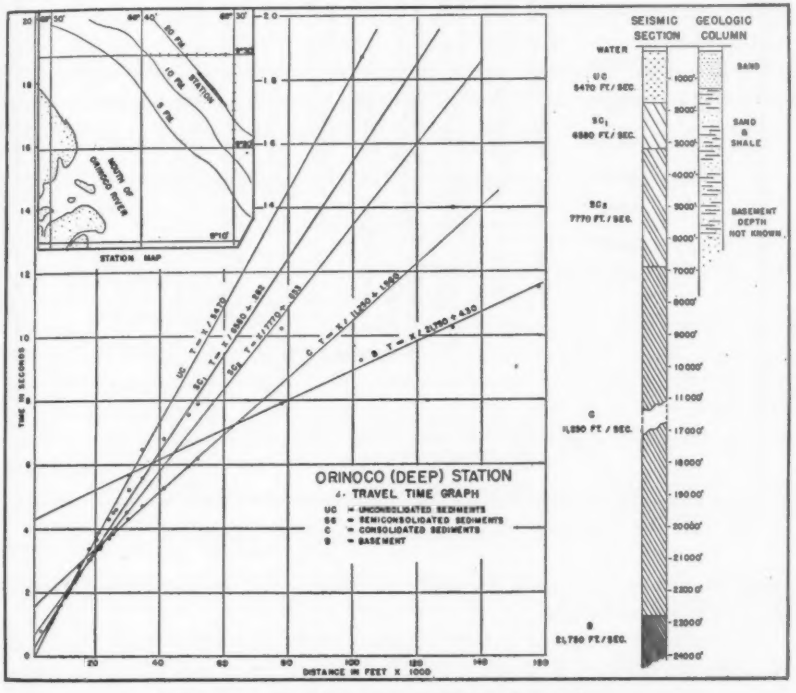


FIGURE 6.—*Travel-time curve for Orinoco deep station*
(a) Station map. (b) Travel-time graph. (c) Seismic and geologic columns

rock has a velocity of 19,560 ft./sec., and the interface between the two is plane over the 10-mile extent of the station. Auxiliary shots on a southerly course show that the plane extends to a point about 4 miles south of Water Island, where it terminates in a steep downslope. This termination occurs about 3 miles inside the 100-fathom curve. The data at this station are excellent.

The Virgin Islands Deep station starts near Outer Brass Island and runs N. 30° W. about 8 miles. The surface rock has a velocity of 12,880 ft./sec. and extends to a depth of 650 feet. An intermediate layer has a velocity of 15,940 ft./sec. and extends to a depth of 2800 feet below sea level. The rock beneath this has a velocity of 18,980 ft./sec. but extends only a little more than 5 miles from Outer Brass Island, or about 6 miles inside the 100-fathom curve, and terminates in a steep downslope.

Auxiliary shots on a westerly course to distances up to 9 miles show that the layer depths remain unchanged along this course. An alternative explanation of the data at this station is that instead of an intermediate layer there is a slope in the surface of the basement layer for about 3 miles in the vicinity of Outer Brass Island. This

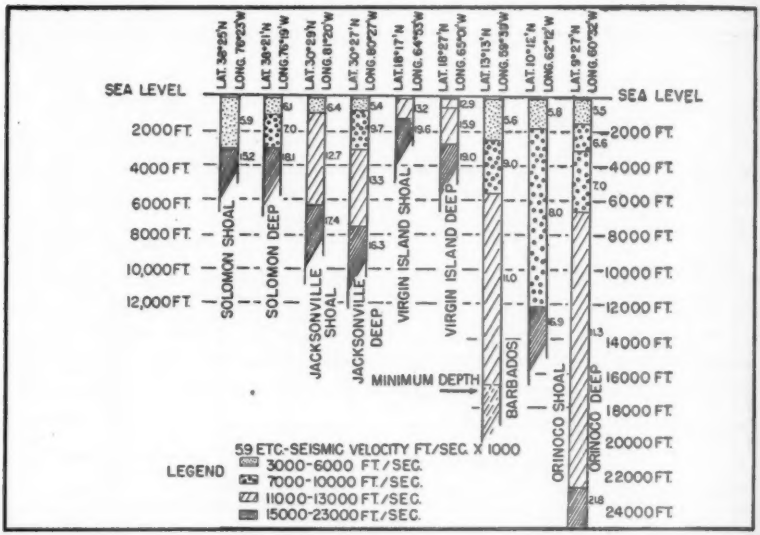


FIGURE 7.—*Depth to basement from seismic measurements*

interpretation would increase the depth to basement but would leave other features of the picture unchanged.

The basement (19,000 ± ft./sec.) found at 1300 feet south of Saint Thomas and at 2700 feet north of it shows a very flat surface which suggests peneplanation. Both of these levels are below the lowest peneplane (near sea level at Saint Thomas) reported by Meyerhoff (1926). This basement is considered to be the igneous complex which forms the basis on which the entire platform is built.

The top layer (velocity 13,000 ft./sec.) is considered to be composed of tertiary and later sediments; the upper part at least is coraline. The values found for the velocities of these two stations again answer in the affirmative the question which has been debated at every proposal of seismic investigations of atolls: Are the velocity relations such that the igneous platform may be detected beneath a coraline cover? The question was first answered in Bermuda, where velocities of 8800 ft./sec. and 16,000 ft./sec. were observed for the coraline cover and for the igneous platform whose depth was about 250 feet (Woollard and Ewing, 1939).

Barbados.—The station made along the western shore of Barbados is of especial interest because that island has a negative gravity anomaly of 134 milligals and lies exactly in the strip of negative gravity anomalies which parallels the West Indian

island arc (Ewing, 1937). The usual interpretation of the negative gravity anomalies, and the fact that all the exposed rocks on Barbados are sediments from both deep and shallow deposition, led to the expectation of a large total thickness of sediments. The seismic profile revealed a velocity of 5620 ft./sec. to a depth of 2600 feet, 9030 ft./sec. to 6100 feet, and 11,040 ft./sec. to an undetermined depth which must exceed 16,600 feet.

Orinoco.—At Orinoco the shoal station was made in the southwest part of the Gulf of Paria, and the depth to basement was 12,200 feet. At the deep station, about 100 miles to the southeast, and in the Atlantic Ocean at the mouth of the Orinoco River the depth to basement was 22,700 feet. There were no available well data to check these seismic determinations.

SEISMIC REFRACTION MEASUREMENTS IN DEEP WATER

CABLE EQUIPMENT USED IN 1937–1938

The seismic measurements made in the Atlantic Ocean basin in 1937–1938 were described at the 1938 meeting of the Geological Society.

The gear as then used was strung along a steel cable. From the ship a steel cable led to a large pressure vessel containing a four-channel oscillograph, from which led a 3400-foot electric cable with four geophones spaced 400 feet apart and three bombs 1000 feet apart. (*See* Figure 8.) Lowerings were made with this equipment; but only one, 180 miles south of Newport, Rhode Island in 1635 fathoms, gave geologic information.

At this station, a bottom velocity of 5700 feet per second was obtained, but basement was not reached. An assumed basement velocity of 18,000 feet per second indicated a depth of sediments greater than 600 feet.

This equipment was unsatisfactory for several reasons:

(1) The oscillograph and geophones would often be affected by unavoidable mechanical disturbances coming down the cable.

(2) When unknown currents opposed the motion of the ship, the gear was often piled on top of itself, instead of being in a line with the proper spacing.

(3) When currents aided the motion of the ship, the gear and the insulation of the of the long electric cables was damaged by dragging on the bottom.

FLOATATION EQUIPMENT USED IN 1939–1940

The cable method was abandoned in favor of a float method, after preliminary calculations and tests. At first it was proposed to lower all of the gear on one float (Ewing and Vine, 1938), using an inclined plane to cause the gear to be laid in a straight line along bottom.

At this stage it was realized that the sounds reaching the geophone from the bomb after one and two surface reflections could be used to calculate the firing time of the bomb without the use of a connecting wire. This point was confirmed by a study of the 1937–1938 records. Plans were then made to lower each bomb and each recording unit on its own float and without any interconnection. (*See* Figure 9.)

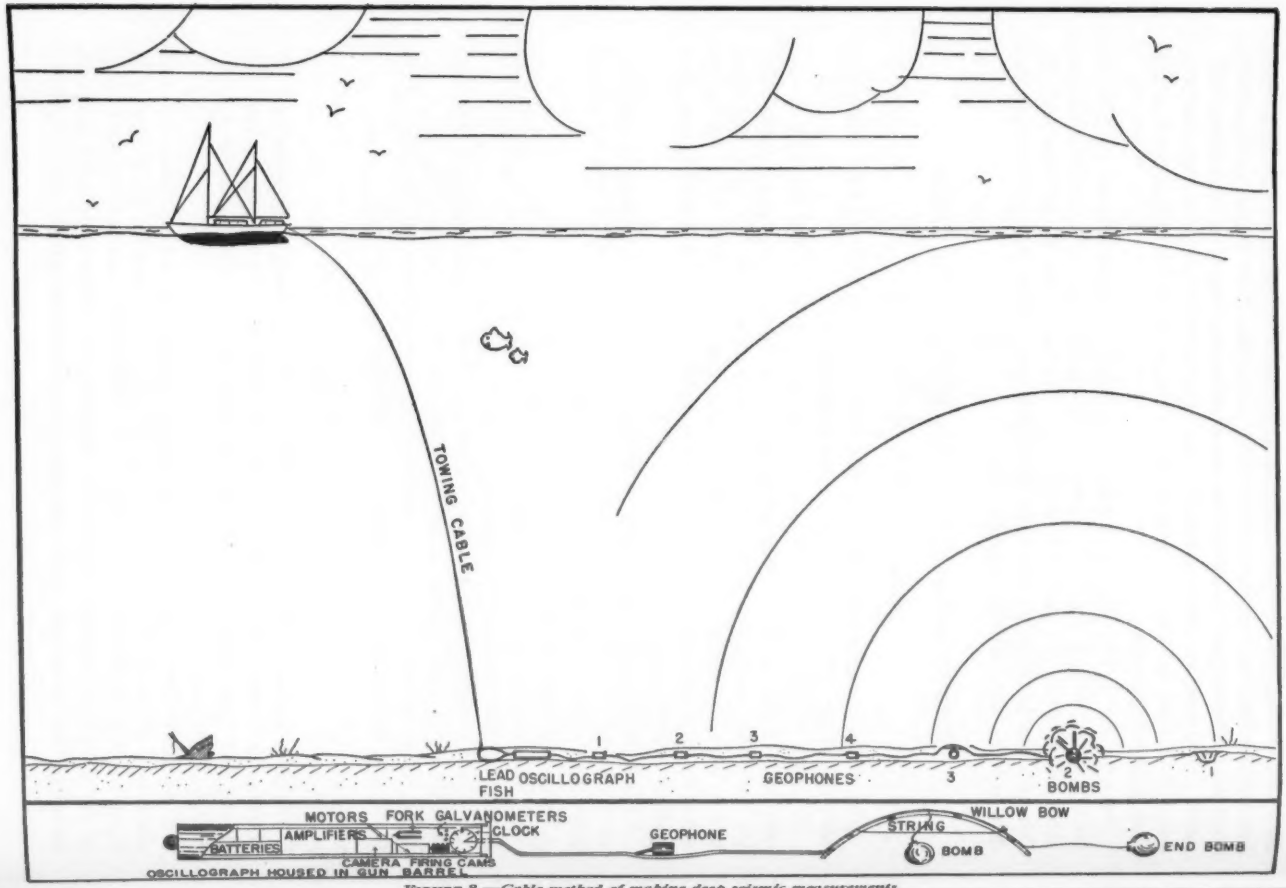


FIGURE 8.—*Cable method of making deep seismic measurements*

OSCILLOGRAPH HOUSED IN GUN BARREL

FIGURE 8.—*Cable method of making deep seismic measurements*

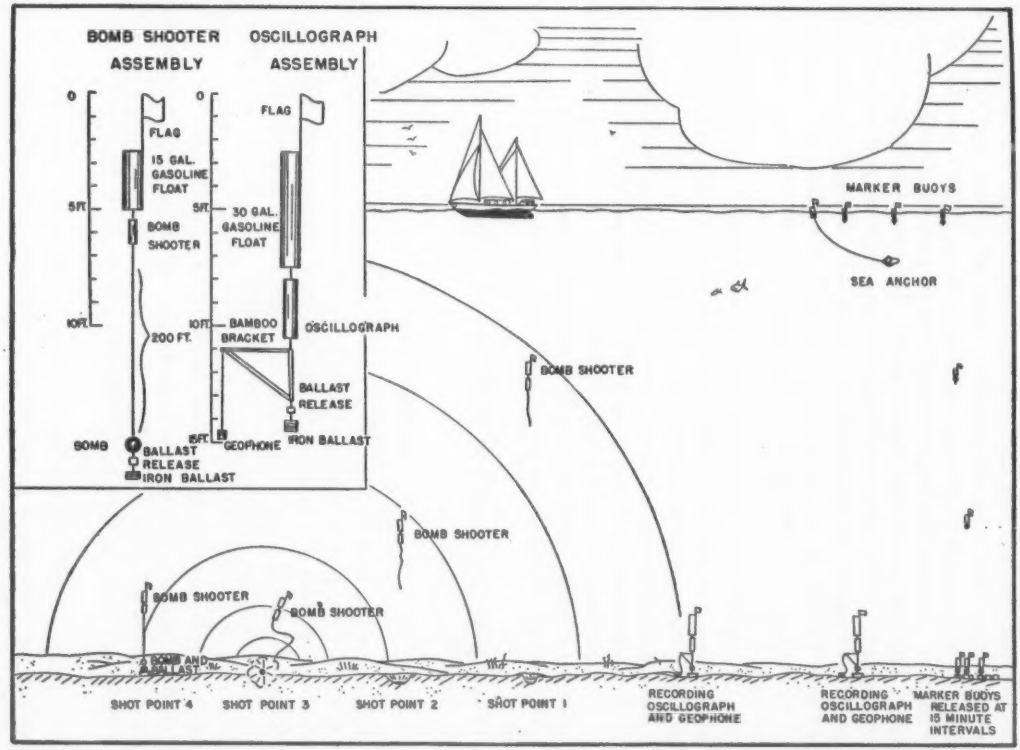


FIGURE 9.—*Float method of making deep seismic measurements*

Each oscillograph was housed in an aluminum pressure case and was lifted by a 30-gallon rubber tank float filled with gasoline. Iron ballast was used to make the assembly sink to the ocean floor where the ballast and the geophone would both rest on the bottom. Synchronized clocks started the oscillograph and fired the bombs in sequence. After the records had been obtained, the ballast was dropped by a release mechanism, and the apparatus floated to the surface where it was recovered. The loss of instruments was reasonably low. Only one oscillograph and nine bomb shooters were lost out of 74 units lowered. Five of these losses were from known causes which have been eliminated. Many pieces of test equipment were also lowered and retrieved.

During the spring of 1939 preliminary tests were made at Bermuda, and the system was further developed in 1940. It eliminated the cable problems and proved to be far superior to the cable method for the following reasons:

(1) The spacing between bombs and oscillographs could be easily extended to provide a station spread sufficient to reach very deep basement.

(2) The work could be done from any seaworthy vessel. Previously, the need for a long cable and special winch had restricted the work to special vessels.

(3) The greatest depths in the ocean could be worked nearly as well as lesser depths.

(4) No one piece of cable was over 200 feet long; this greatly facilitated the handling of the gear.

1940 OPERATIONS

In 1940, operating from Woods Hole in the ATLANTIS, a station was occupied 140 miles south of Cape Cod, Massachusetts, in 1400 fathoms of water.

The record obtained (Pl. 7) shows the ground wave, direct water wave, and the first and second echoes from the surface. This station had a spread of 4200 feet, and a bottom velocity of 5400 ft./sec. was obtained. No indication of high-speed basement rock was on the record. Assuming 18,000 ft./sec. for basement velocity, the depth of sediments was calculated to be greater than 1500 feet.

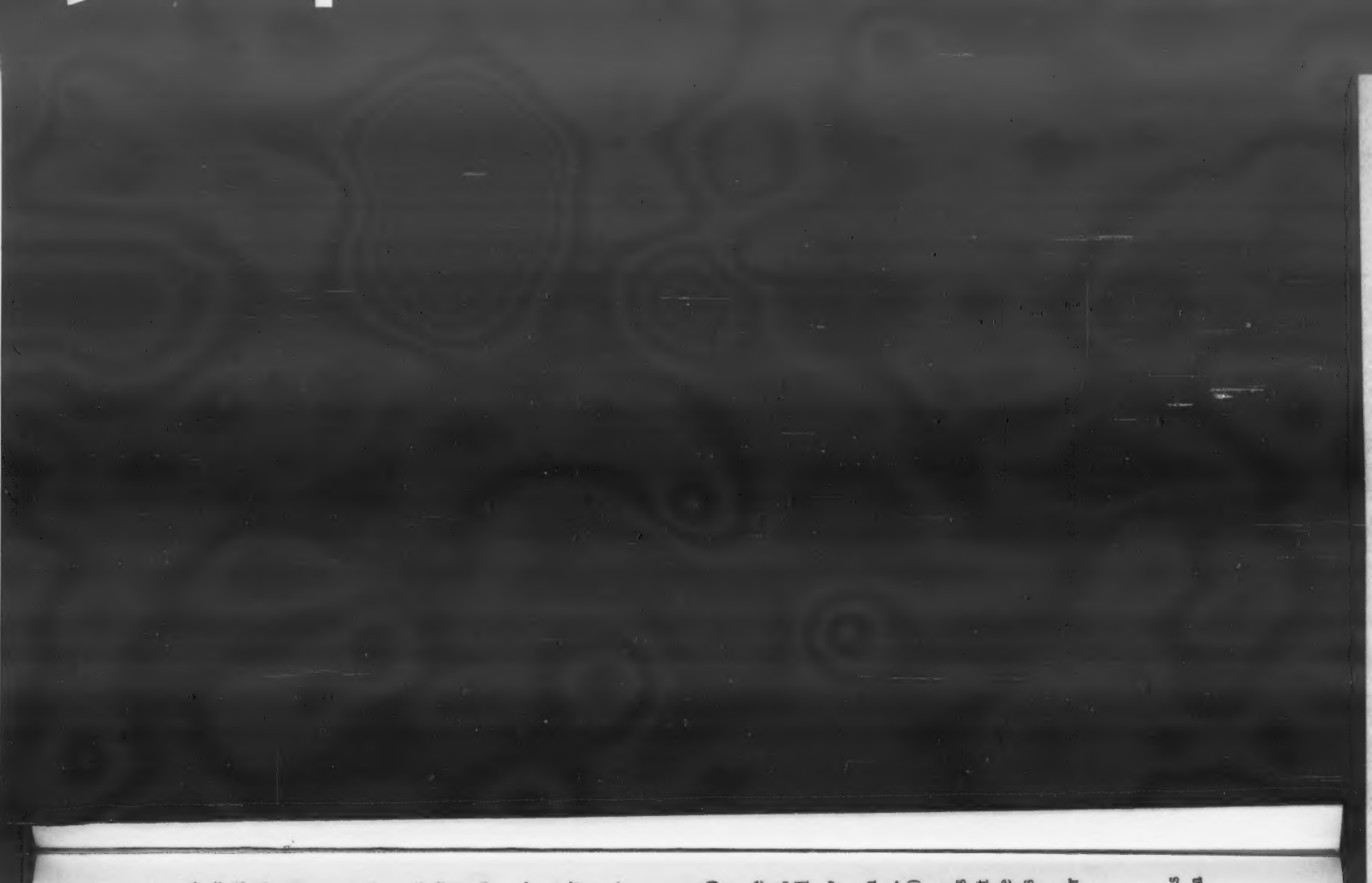
Later in the summer, a station was occupied 300 miles northwest of Bermuda in 2600 fathoms with a spread of 3300 feet. A velocity in the bottom of 5300 ft./sec. was obtained, and the thickness of sediments was calculated to be greater than 1200 feet.

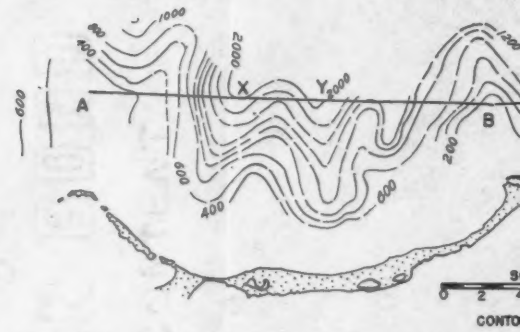
It is unfortunate that, due to minor instrumental difficulties, only one bomb was recorded by one oscillograph at each station. However, these difficulties were not fundamental, and the quality of the records obtained proved the feasibility of the method. At this point the war stopped the investigations before other stations could be occupied.

We consider that a satisfactory method of shooting refraction profiles on the floor of the ocean has been developed.

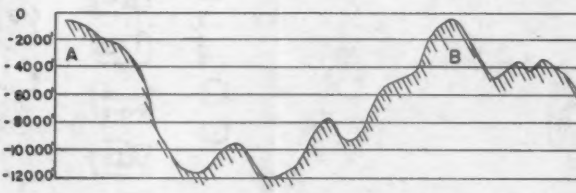
ELEUTHERA ISLAND BATHYMETRY

A reconnaissance survey of the offshore slope of Eleuthera Island, Bahamas (Pl. 6) has been made by the U.S.C.G.R. VALOR. The soundings were made with a

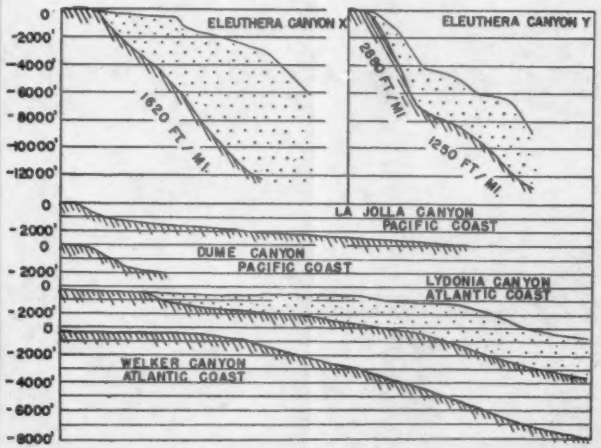




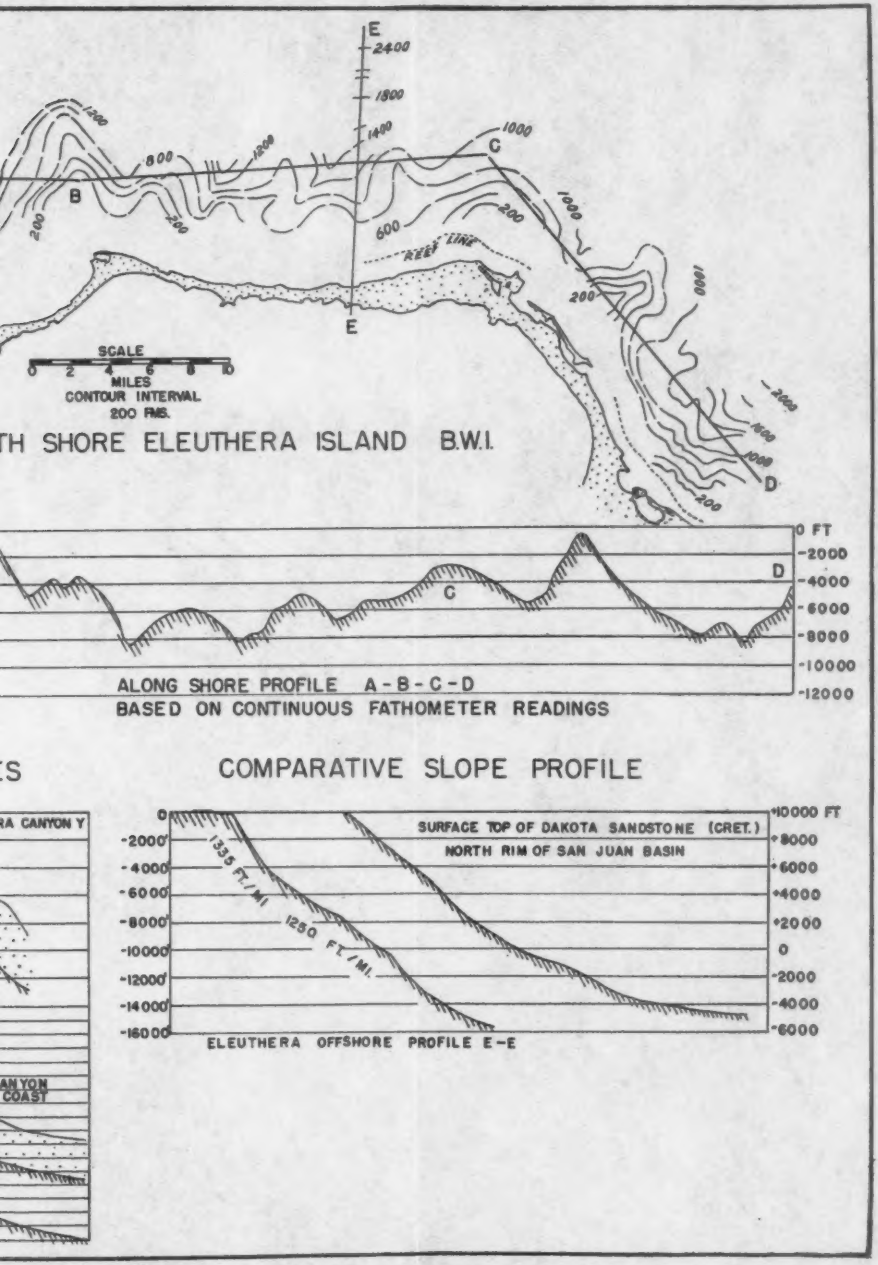
SUBMARINE CONTOURS NORTH SHOR



COMPARATIVE CANYON PROFILES



BATHYMETRIC CH
Vertical exa



IETRIC CHART OF ELEUTHERA ISLAND
Vertical exaggeration in profiles is 3½

fathometer and have not been corrected to vertical soundings. Positions of the soundings relative to the beach were fixed with radar.

Conservative contours were drawn to fit the soundings. The solid-line portions have good control, while the dashed portions are less certain. Beneath the contoured chart is a section parallel to the shore line showing a variation of depth as large as 12,000 feet. This traverse follows a line of continuous soundings.

The topography is complicated by the numerous canyons which furrow the steep slope to depths greater than 12,000 feet. These canyons have much steeper slopes than those of either coast of the United States (Pl. 6). The general seaward slope is about 1300 feet per mile, which is the same order of magnitude as that given by Hess (1933) for the walls of the Tongue of the Ocean. However, the break in slope which he found at about 4000-foot depth was not observed on the eastern slope of Eleuthera. In Plate 6, the general seaward slope of Eleuthera along section EE is comparable with that of the top of the Dakota sandstone across the northern rim of the San Juan Basin, one of the steepest structural profiles on the tectonic map of the United States.

NEW METHOD OF SAMPLING THE OCEAN BOTTOM

During the past 3 years, several thousand bottom samples have been obtained on the continental shelf with a newly developed bottom sampler. The new sampler can be used underway at speeds of 8 knots or more, thus enabling large areas to be covered. The operation of the instrument is so simple that the time for lowering ranges from about 8 minutes in 100 fathoms of water to about 3 minutes in 10 fathoms. These features permit more detailed sampling than is possible with previous samplers (Hough, 1939) which required the vessel to be stopped. Because the ship's speed and course are not altered, the relative positions of stations are also greatly improved.

The instrument (Fig. 10) is simple and inexpensive; it consists of a brass or iron weight with fins on the tail and a sampling tube on the nose. The hoisting cable is attached just forward of the center of gravity.

While descending, the cable is allowed to pay out faster than the ship moves ahead, thus permitting the sampler to fall. The tail fins cause the sampler to strike bottom nose first. Bottom contact is indicated by the cable going slack. The brake is applied, the cable becomes taut, the sampler rises and is reeled in. This type of operation has proven very reliable; for in some 1200 bottom samples taken by our group, instrument losses have been negligible.

The size of the sample obtained in a lowering is about half a pint, although a bigger sampler could be made to obtain larger samples and to operate at greater depths. The depth of penetration was several inches, and the sampler functioned satisfactorily in mud, sand, gravel, and has even brought up considerable coral. Other models which had trap doors to confine the sample and eliminate washing have been built and successfully operated. However, as samples taken with the original instrument showed little tendency to wash, the trap-door models were seldom used.

The ability to take samples underway is a particular advantage if the vessel is

equipped with a continuously recording fathometer, because the position from which the sample is taken can be accurately located with relation to the bottom topography. An attachment has been built into some samplers to record the depth at which each sample is taken.

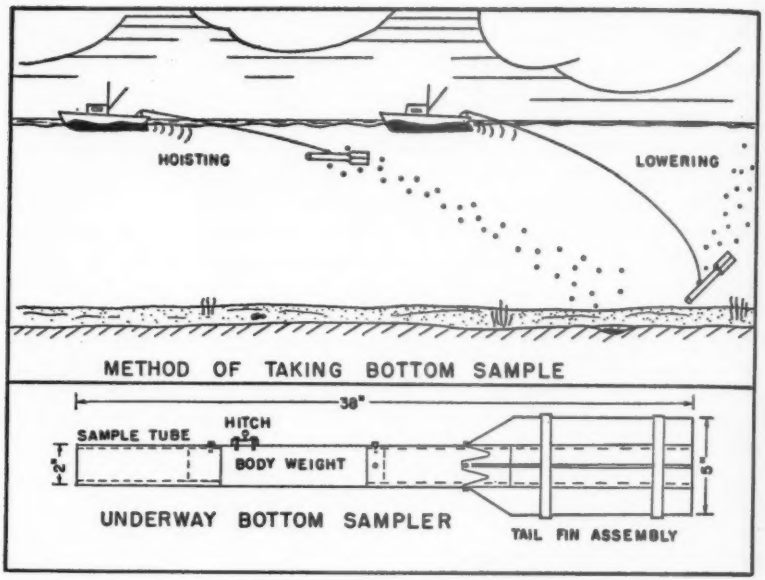


FIGURE 10.—*Bottom sampler*

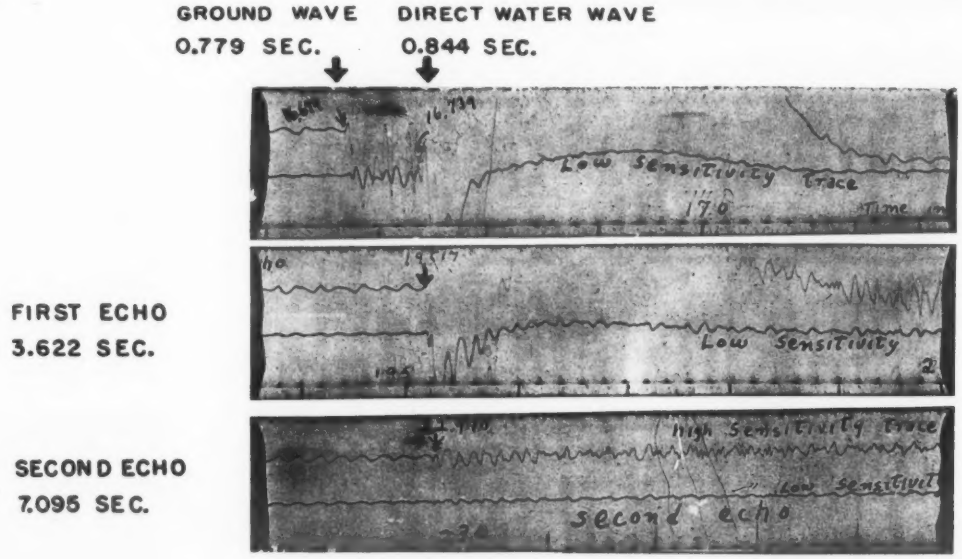
(a) Method of taking a bottom sample. (b) Underway bottom sampler

PHOTOGRAPHY OF THE OCEAN BOTTOM

GENERAL STATEMENT

During the war, the methods of underwater photography previously developed at the Woods Hole Oceanographic Institution have been applied to several military problems, most of which are not of geologic interest. The war-time activity has resulted in an increase in the number of cameras and trained operators available, in minor improvements in instruments and operating techniques, and has produced about 100 useful photographs of the bottom.

Although various types of under-water cameras have been used, the most common type was mounted on a wooden pole, about 10 feet in length, weighted at the bottom to keep it erect. Thus, when the camera was lowered on floats or on a line, it always pointed downward. A trigger weight was suspended below the camera at the distance for which the camera was focused. When the trigger weight struck bottom, the shutter was tripped, and a flash bulb fired (Fig. 11).



DEEP SEISMIC STATION 1460 FATHOMS

140 MILES SOUTH OF CAPE COD, MASS.

25 JULY 1940 LAT. 39°21'N LONG. 70°40'W

SEISMOGRAMS FROM DEEP SEISMIC MEASUREMENTS
July 25, 1940, 1460 fm., 39°21′ N., 70°40′ W.

FIGURE 1. STONY BOTTOM.
Position: 42°09′N., 66°30′ W., depth: 324 ft., date: 6/24/40, camera to bottom: 7.1 ft.

FIGURE 4. SAND RIPPLES.
Position: 34°41.5′N., 75°35.1′W., depth: 390 ft., date: 8/11/42, camera to bottom: 12 ft.

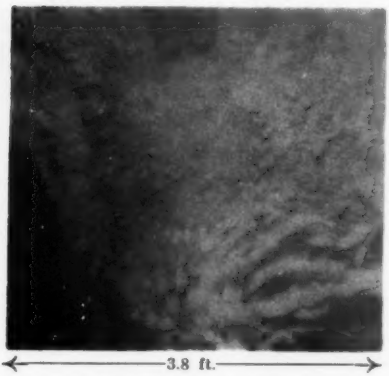


FIGURE 2. ROCK BOTTOM.
Position: 41°18′ N., 70°51.4′ W., depth: 36 ft., date: 9/1/42, camera to bottom: 4 ft.

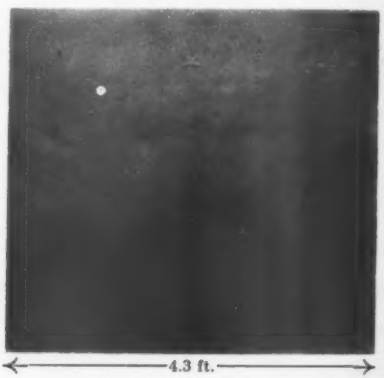


FIGURE 5. MUD BOTTOM.
Position: 40°09′ N., 71°22′ W., depth: 300 ft., date: 10/9/41, camera to bottom: 7 ft.

FIGURE 3. CORAL BOTTOM.
Position: 24°56′ N., 76°08′ W., depth: 36 ft., date: 8/11/43, camera to bottom: 12 ft.

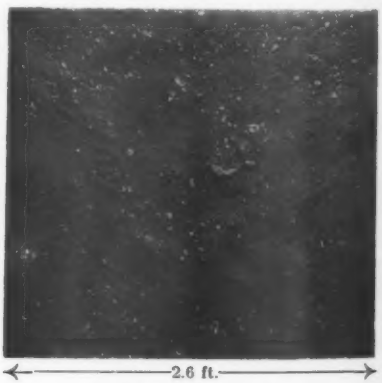


FIGURE 6. SAND-MUD BOTTOM.
Position: 40°41′ N., 67°02′ W., depth: 432 ft. date: 6/21/40, camera to bottom: 7.1 ft.

PHOTOGRAPHS OF TYPES OF OCEAN BOTTOMS

GEOLOGICAL INFORMATION FROM UNDER-WATER PHOTOGRAPHS

The type of geological information given by photographs of the bottom can best be illustrated by typical pictures.

The general type of bottom, such as rocky, stony, coral, sand, or mud is the most important and most easily recognized feature (Pl. 8).

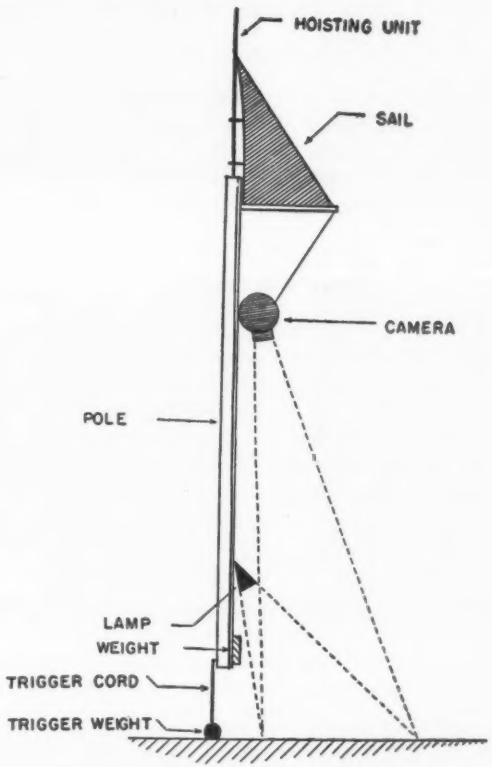


FIGURE 11.—*Schematic diagram of under-water camera*

As these photographs cover from 10 to 1000 square feet of bottom, they give a much truer picture of conditions than a single bottom sample. For example, in a small area near Boston Lightship where numerous bottom samples had shown only mud, a bottom photograph showed the contact between a stony area and a rocky area, both covered with a thin layer of mud (Pl. 9, fig. 4).

Physical peculiarities of the bottom that would be missed by other methods are shown by photographs. For example, various types of sand ripples are shown in Figures 5 and 6 of Plate 9.

An estimate of the compaction of the bottom can often be made from the depth to

which the trigger weight sinks into bottom or from the size of the silt cloud sometimes formed when the trigger weight strikes. The latter is plainly shown in Figure 1 of Plate 9.

The concentration of marine organisms or of shells over an area of the bottom can be determined. Various concentrations of marine life are illustrated in Plate 10.

LONG-RANGE SOUND TRANSMISSION IN THE OCEANS

GENERAL STATEMENT

By taking advantage of the refractive properties of the water it has been possible to transmit acoustical signals through the water to distances which vastly exceed anything previously thought possible. Recently, a small bomb dropped off Dakar in Africa was heard on Eleuthera Island in the Bahamas—about 3100 miles away. No other man-made sound has been heard at more than a small fraction of this distance.

REFRACTION EFFECTS

An examination of the thermal structure (Fig. 12) of North Atlantic water at typical stations shows that the temperature decreases rapidly from the surface to a depth of about 4000 feet and then remains relatively constant to bottom. As a result (Fig. 13) the velocity of propagation of sound decreases, due to the temperature decrease, from surface to 4000 feet and then increases, due to the pressure increase, from there to bottom. This type of velocity pattern is known as a sound channel and may be used to great advantage in sound transmission. The depth of minimum sound velocity is known as the axis of the sound channel.

When sound travels in a medium in which the velocity changes with depth, the sound rays are refracted according to Snell's Law. In the present case, theyare bent downward above the axis of the sound channel and upward below the axis. Sound rays may be bent back and forth across the depth of minimum velocity so that they may travel to very great distances without reflection from surface or bottom. A calculation has been made to determine the paths of rays from a sound source located at the sound-channel axis. (*See* Pl. 11.) It is found that all rays having initial inclinations less than about 12° are sufficiently refracted that they never encounter surface or bottom. Such rays are known as sound-channel rays. The effect of the sound channel may be compared to that of a speaking tube.

SIGNAL STRUCTURE

Plate 11 shows that there are many different rays along which the sound may reach a distant receiver located on the axis of the sound channel. Those rays with large initial inclinations reach almost to surface and bottom on each oscillation and make relatively few oscillations across the axis of the channel. The rays with small initial inclinations make many small oscillations and remain relativel ynear the axis.

Although those rays which remain near the sound-channel axis have a slightly shorter actual path to travel, they are the last to arrive at a given point because

FIGURE 1. SOFT BOTTOM.
Position: 40°31′ N., 67°35′ W., depth: 438 ft.,
date: 6/21/40, camera to bottom: 7.1 ft.

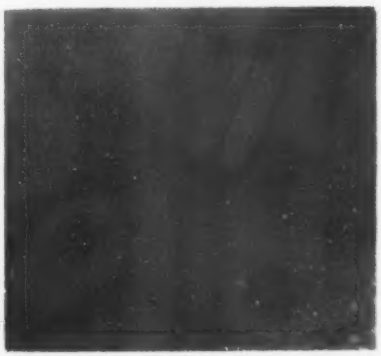


FIGURE 2. FIRM BOTTOM.
Position: 41°12′ N., 72°33′ W., depth: 60 ft.,
date: 9/2/42, camera to bottom: 4 ft.

FIGURE 3. COMPOSITE BOTTOM.
Position 42°08′ N., 67°12′ W., depth: 384 ft.,
date: 6/25/40, camera to bottom: 7.1 ft.

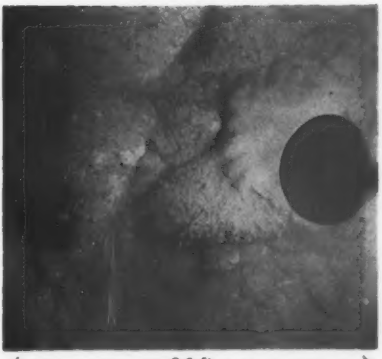
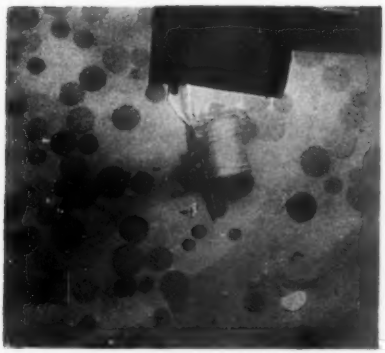


FIGURE 4. COMPOSITE BOTTOM.
Position: 42°23′ N., 70°44′ W., depth: 96 ft.,
date: 8/1/45, camera to bottom: 5.8 ft.

FIGURE 5. SAND RIPPLES.
Position: 41°55′ N., 66°47′ W., depth: 222 ft.,
date: 6/24/40, camera to bottom: 7.1 ft.

FIGURE 6. SAND RIPPLES.
Position: 41°06′ N., 67°25′ W., depth: 192 ft.,
date: 6/25/40, camera to bottom: 7.1 ft.

PHOTOGRAPHS SHOWING COMPACTION, COMPOSITE BOTTOMS, AND SAND RIPPLES



6 ft.

FIGURE 1. SAND DOLLARS.
Position: 43°28′ N., 70°06′ W., depth: 60 ft.,
date: 3/21/42, camera to bottom: 8 ft.

4.6 ft.

FIGURE 2. SEA PENS.
Position: 40°09′ N., 71°22′ W., depth: 300 ft.,
date: 10/9/41, camera to bottom: 7 ft.

2.5 ft.

FIGURE 3. MUSSEL BED.
Position: 41°31′ N., 70°39′ W., depth: 36 ft.,
date: 10/23/42, camera to bottom: 4 ft.

4.3 ft.

FIGURE 4. STAR FISH COLONY.
Position: 41°15′ N., 71°57′ W., depth: 110 ft.,
date: 5/10/42, camera to bottom: 7 ft.

2.0 ft.

FIGURE 5. BOTTOM GROWTH.
Position: 40°24′ N., 71°05′ W., depth: 18 ft.,
date: 9/3/42, camera to bottom: 4 ft.

2.0 ft.

FIGURE 6. BOTTOM GROWTH.
Position: 41°21′ N., 71° 04′W., depth: 30 ft.,
date: 9/3/42, camera to bottom: 4 ft.

PHOTOGRAPHS OF PLANT AND ANIMAL LIFE ON THE SEA FLOOR

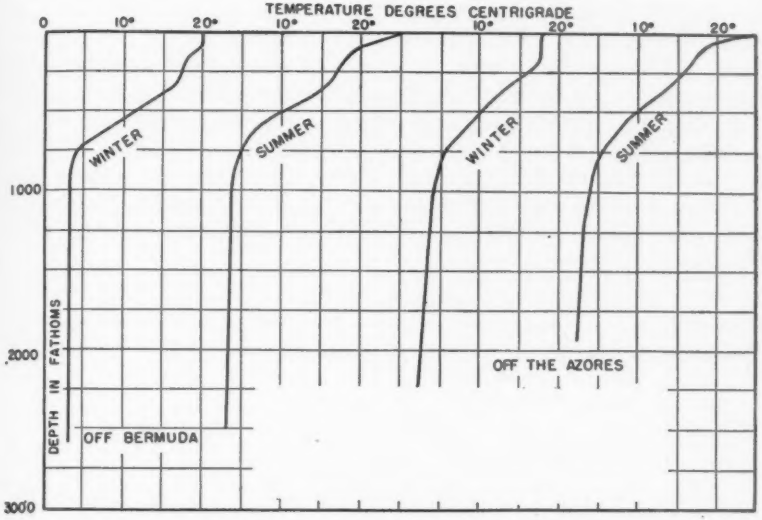


FIGURE 12.—*Typical temperature-depth curves in the North Atlantic ocean*

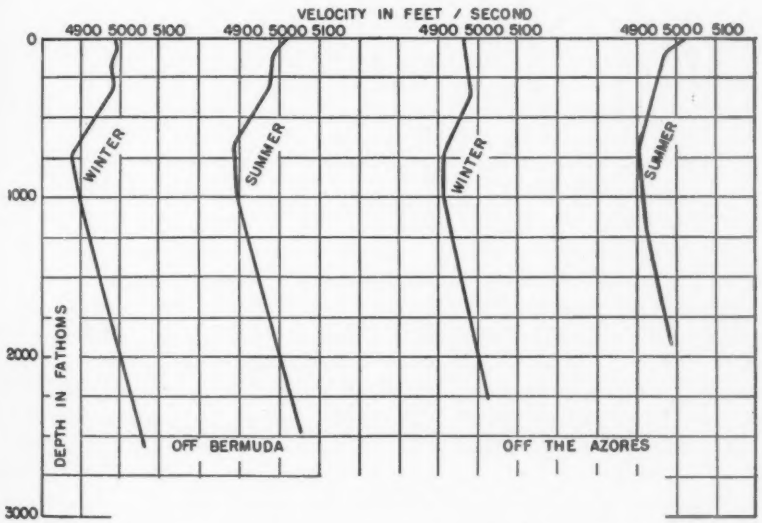


FIGURE 13.—*Typical velocity-depth curves in the North Atlantic ocean*

their entire path lies near the depth of minimum sound velocity. Calculation shows that the mean or effective velocity varies from 4890 feet per second for the axial rays to 4960 feet per second for those rays which reach practically to the surface.

This is a variation of about 1 per cent. If we consider as an example a shot at a distance of 1000 miles, the travel time is about 20 minutes. This difference in velocity causes an explosion sound to spread out into a signal whose duration is about 12 seconds at 1000 miles. As a result, the signal has a highly recognizable pattern (Fig. 14). It sounds like kettle drums, starting very gradually and faintly. The tempo and the intensity both increase to the very end of the signal, which is an abrupt cut-off from maximum intensity to complete silence. This abrupt cut-off is useful because it is a sharp feature whose arrival can be timed to better than 1/10 second. This feature is well illustrated in Plate 12, an actual record for a shot at 300 miles.

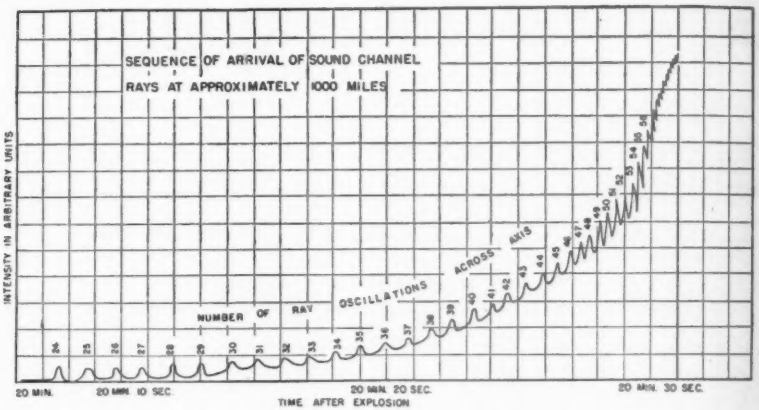
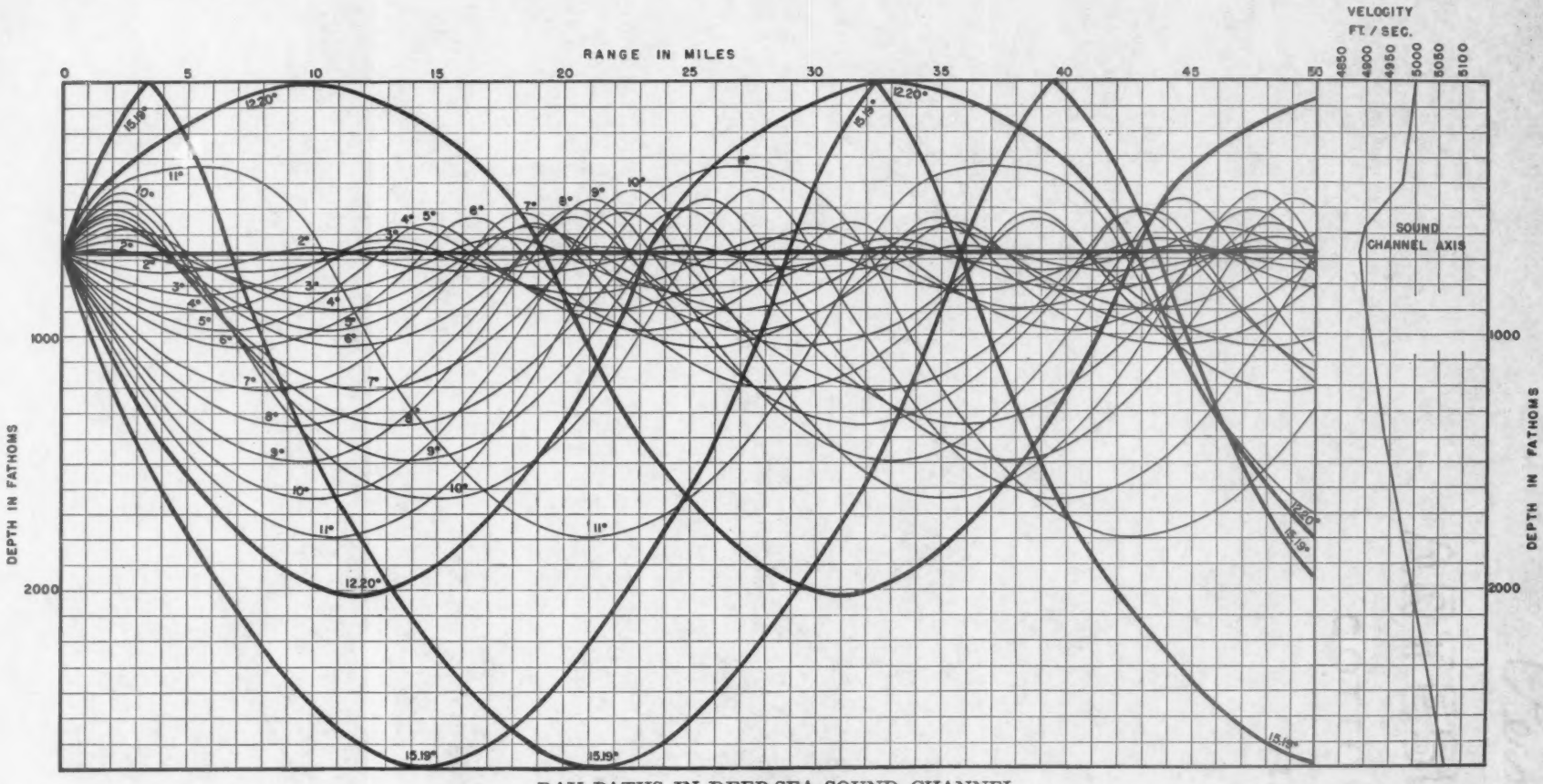


FIGURE 14.—*Sequence of arrival of sound channel rays at approximately 1000 miles*

PRACTICAL APPLICATIONS

The means for generating and receiving signals have been reduced to reasonable simplicity. A bomb which explodes hydrostatically at the axis depth can be made for a few dollars. The signals have been received on shipboard by lowering the hydrophone to the sound-channel axis and at a shore installation by leading a cable from the beach to this depth. The shore-based installation is far more reliable for operation in all types of weather. Signals received at shore-based stations are somewhat complicated by reflections from the sloping bottom, but the essential features remain, and the signals are perfectly satisfactory.

Three major geologic applications to sound-channel transmission have been considered: position fixing, submarine volcano location, and discovery of shoal areas. Reception at two receiving stations whose positions are known will provide a fix of the sound source, provided the time of the explosion is known accurately. Reception at three stations provides a fix and also gives the time of the explosion. These fixes are accurate to about a mile, and in all probability the error can be reduced. Here we



RAY PATHS IN DEEP-SEA SOUND CHANNEL

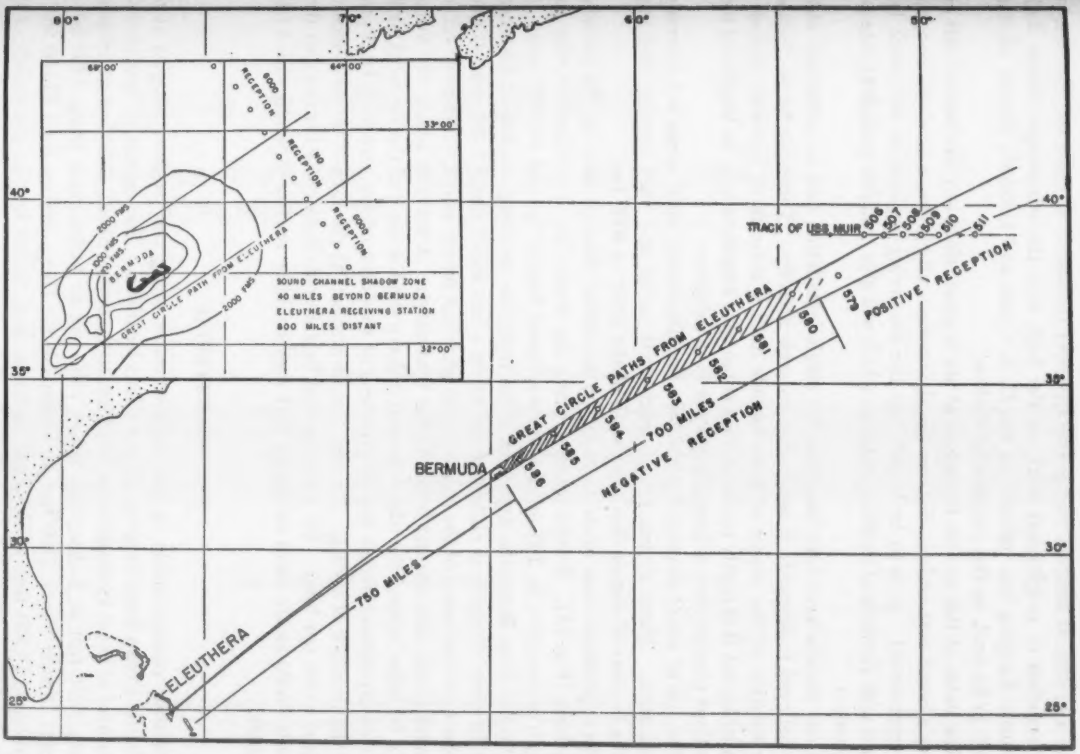


FIGURE 15.—*Shadow zone at Eleuthera for Bermuda Island*

have a system of location that is effective over thousands of miles and can bring to all branches of geophysical work on the high seas the advantages which Radio Acoustic Ranging has brought to the U. S. Coast and Geodetic Survey (Adams, 1942) in its work on the continental shelves.

The value of this system for rescue at sea is great, since any life boat or raft can carry a bomb with which a distress signal, automatically giving a fix of position, may be transmitted. It is to be hoped that the life-saving application will result in a world-wide network of receiving stations which will give valuable geological data as a byproduct.

Some sounds have been heard on the single installation now in operation[2] which are believed to originate in submarine volcanic activity. There can be no check on the location of the source of these sounds until a network of listening stations is available, but it is highly probable that submarine eruptions may be heard and their positions plotted once a listening system is in existence.

The use of sound-channel transmission for discovering shoal areas is a promising application. These signals travel great-circle paths, and they require that these paths be clear of obstruction to a depth of the order of 4000 feet.

An experiment was made to map the acoustical shadow cast by the Bermuda Platform (Fig. 15). Bombs dropped along the center line of the shadow zone gave negative reception to 700 miles and were heard faintly beyond this distance. At 900 miles from Bermuda, and 1650 miles from the receiving station at Eleuthera, bombs were dropped at close spacing along a line which crossed the shadow zone. Those near the center of the shadow zone were just barely heard, while those outside it were heard with normal intensity for that range. A traverse across the shadow zone 40 miles beyond the island showed a sharp shadow zone of the expected width.

This experiment shows the effectiveness of this method for searching large areas for the presence of shoals. An area can be scanned at the rate of several thousand square miles per hour. By using several listening stations cross bearings on these shoals would locate them so closely that they could be readily explored with a fathometer.

CONCLUSIONS

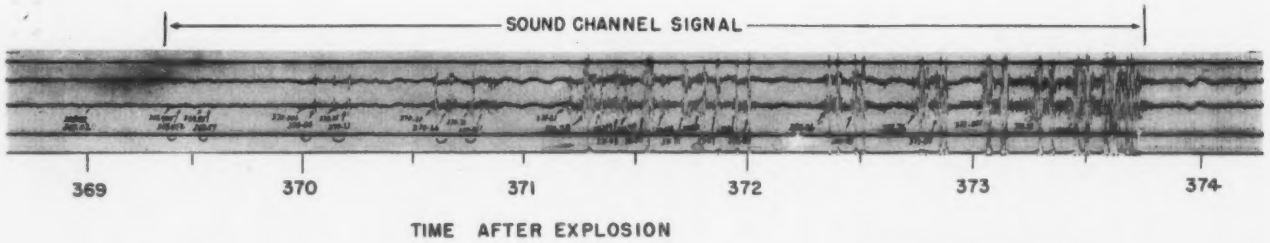
Seismic measurements in the shallow water along the western margins of the Atlantic Ocean have been made at various locations. The depths to basement determined at these locations were 3050 feet at Solomons Shoal, 2950 feet at Solomons Deep, 6250 feet at Jacksonville Shoal, 7600 feet at Jacksonville Deep, 1300 feet at Virgin Islands Shoal, 2700 feet at Virgin Islands Deep, greater than 17,000 feet at Barbados, 12,200 feet at the Gulf of Paria, and 22,700 feet at the mouth of the Orinoco River. The values at Jacksonville and Solomons are in reasonable agreement with the best available well data. No well data were available at the other stations.

Multiple sound waves from the oscillations of the gas bubble resulting from an explosion may lead to confusion in interpreting seismic records. These oscillations may be avoided by placing the charge above a critical depth.

[2] Installation abandoned December, 1945, Navy orders.

OSCILLOGRAPH RECORDING

4 LB. BOMB, 4000 FT. DEEP, 300 MILES AWAY
HYDROPHONE 3600 FT. DEEP



SEISMOGRAM OF SOUND-CHANNEL TRANSMISSION AT 300 MILES
4 lb. bomb; bomb depth 4000 ft.; hydrophone depth 3600 ft.

Frequency dispersion in shallow water was noted. This phenomenon may be used to determine the properties of the bottom to a depth approximately equal to the water depth. It is believed that this phenomenon can be used in deep-water investigations.

Deep-water seismic observations were made with equipment lowered by cables and by floats. Analysis of surface echoes makes it possible to determine the relative times without other communication at all recording units.

Two stations occupied in 1500 fathoms and one in 2600 fathoms showed the surface layer of the bottom to have approximately the same sound velocity as the weathered surface layer on land. The records indicate that sediments are more than 600, 1200, and 1500 feet thick at these stations.

Using a new method, the ocean bottom may be sampled from ships underway at speeds up to 8 knots. More accurate location of the source of samples is possible, and a greater area may be sampled in the same time than with other instruments. A depth recorder has been used by a simple addition to the instrument so that the depth at which the sample was taken could be determined.

A bathymetric chart of the offshore slope on the Atlantic side of Eleuthera Island, Bahamas, was obtained. Two profiles of submarine canyons show that they are deeper and more precipitous than canyons along the east and west coasts of the United States.

The use of under-water photography is an aid in geological observations of bottom materials, sand ripples, compaction of sediments, and distribution of life.

Long-range sound transmission was found in the natural sound channel of the oceans. Utilizing this feature, the sound from a 6-pound TNT bomb was heard at ranges as great as 3100 miles. The interference of an island structure, such as Bermuda, between the shot and the receiver was observed. Certain noises which have been heard while monitoring for shots are tentatively attributed to submarine volcanic activity. Three receiving stations may be used to locate a bomb with an accuracy of about a mile.

A network of stations will probably be set up to utilize the life-saving applications of this system. It is hoped that the useful geologic applications of position finding for survey vessels, location of shoals by scanning methods, and location of submarine volcanic activity may be available as byproducts.

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Department of Geology, Columbia University, N. Y 27, N. Y.; Woods Hole Oceanographic Institution, Woods Hole, Mass.

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Contribution No. 351, Woods Hole Oceanographic Institution

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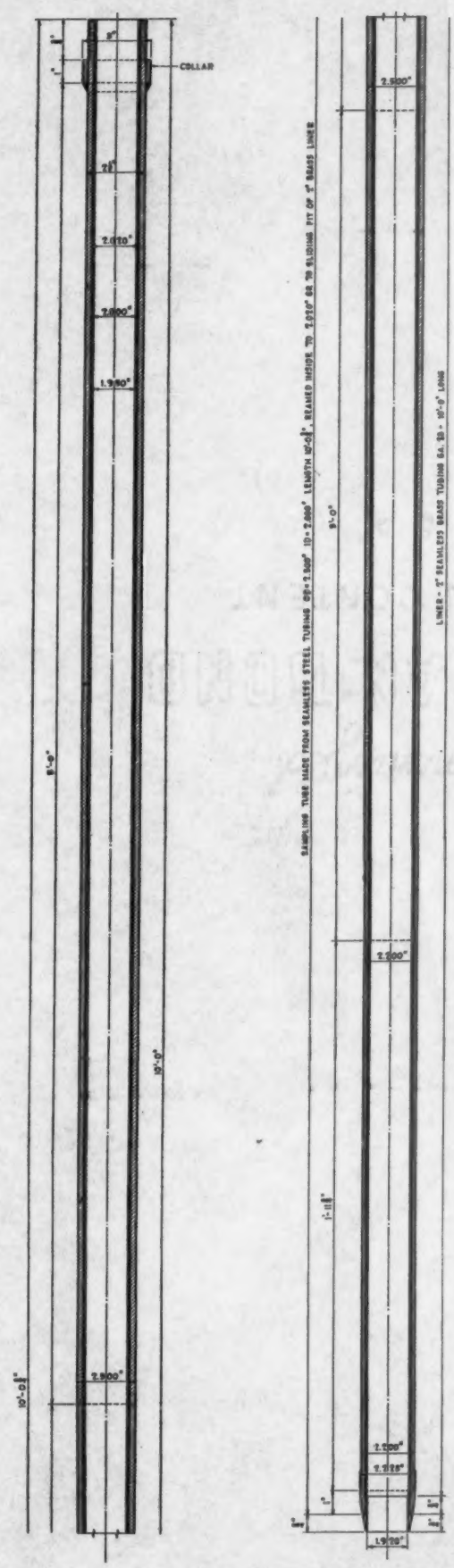

SAMPLING TUBE
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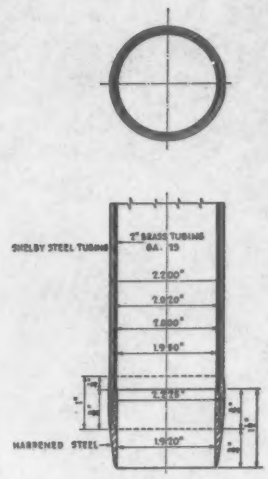

CUTTING EDGE
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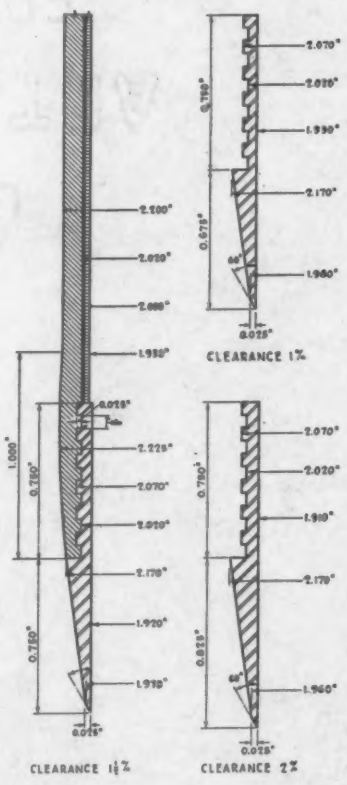

DETAILS OF THE CUTTING EDGES
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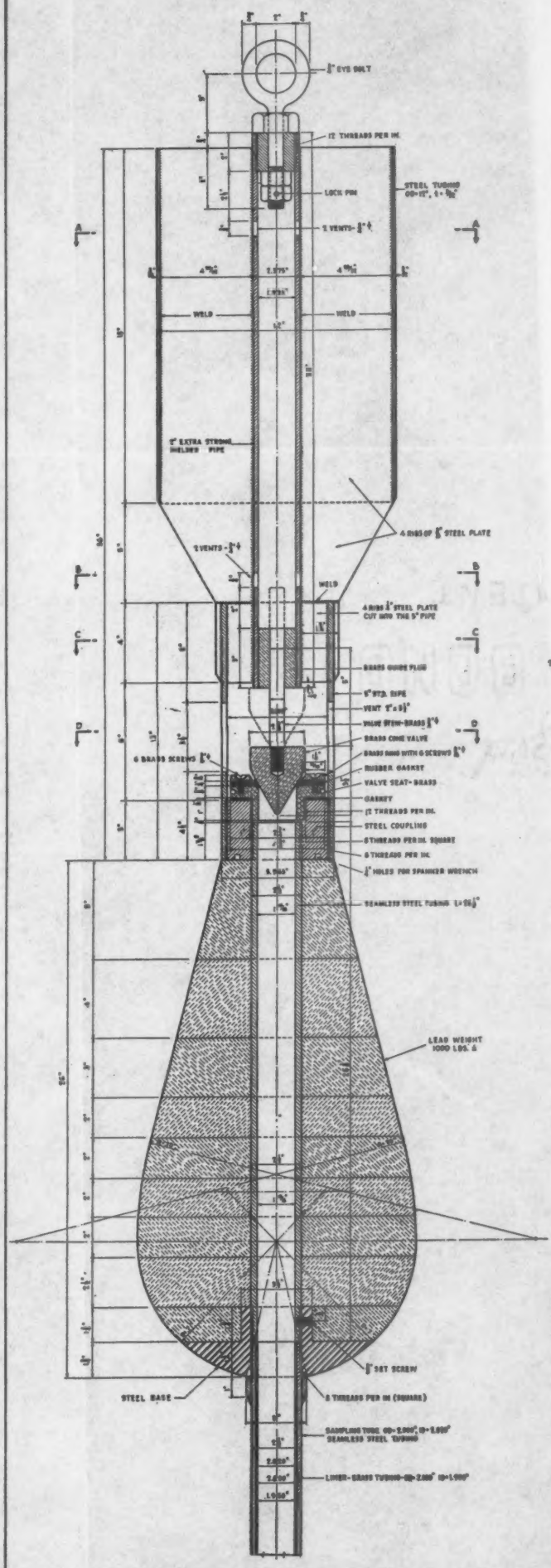

DRIVE WEIGHT, CHECK VALVE AND GUIDE VANES
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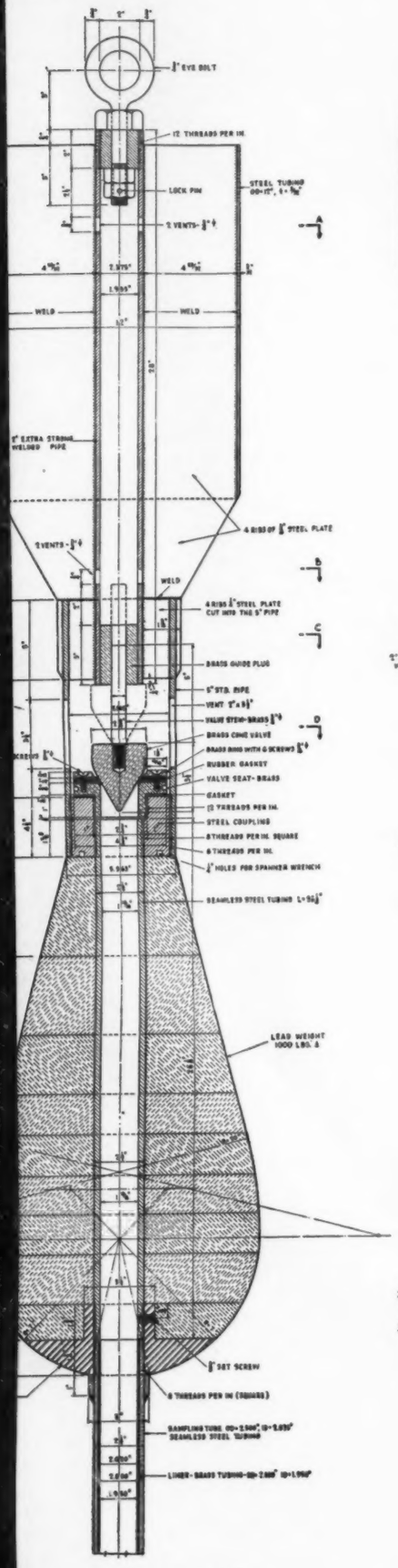

WEIGHT, CHECK VALVE AND GUIDE VANES

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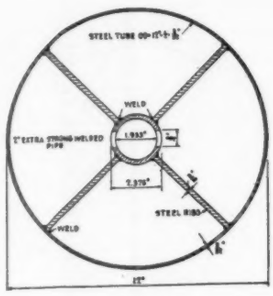

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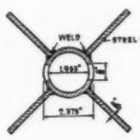

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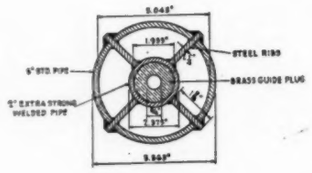

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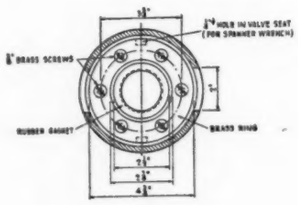

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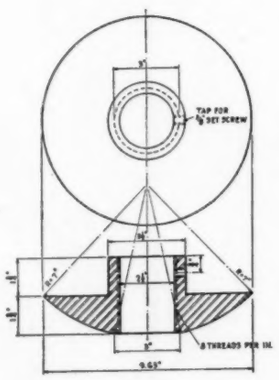

DETAILS OF STEEL BASE

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VOL. 57, PP. 935-950, 4 PLS., 4 FIGS. OCTOBER 1946

FREE-FALL CORING TUBE: A NEW TYPE OF GRAVITY BOTTOM SAMPLER

BY M. JUUL HVORSLEV AND HENRY C. STETSON

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ABSTRACT

A new method of operating gravity-coring tubes has been developed and tested. By means of a pilot weight and release mechanism, the coring tube with drive weight and guide vanes is released at a predetermined distance above the sea bottom and allowed to drop freely through the water. It thereby gains considerable velocity and momentum, and the energy available for forcing the tube into the sediments may be increased in this manner. This method of operation has proved to be especially valuable in coring firm sediments, in which hitherto it has been difficult to obtain a satisfactory depth of penetration with a coring tube whose downward velocity is governed by the safe speed at which a cable may be payed out. Two coring tubes of this type have been built for the Woods Hole Oceanographic Institution, and cores of bottom sediments obtained in the North Atlantic Ocean at depths up to 2250 fathoms. The general theory and details of construction and operation and some of the results obtained are described.

INTRODUCTION AND ACKNOWLEDGMENTS

The coring tubes used in early explorations of the bottom sediments of the oceans were all of the simple gravity type. The coring tube with attached iron or lead weights was lowered at the maximum safe speed at which the cable may be unreeled, generally 3 to 5 ft./sec. This method is still employed with many of the currently used coring tubes, and it provides satisfactory penetration of the tube into fairly soft but not into coarse or somewhat consolidated sediments. As will be shown later, the kinetic energy gained by a velocity of 3 to 5 ft./sec. constitutes only a very small part of the energy used in forcing the tube into the sediment. By far the largest part of the energy is the potential energy furnished by the weight of the tube and attached drive weights, and this weight is limited by the capacity of the winch and the strength, length, and weight of the cable paid out, and the additional force required to withdraw the tube from the sediment.

To supply additional energy, required for greater penetration into firm sediments, Piggot (1936; 1941), developed a sampler in which the coring tube is attached to a short, heavy gun barrel and is forced into the sediment by means of explosives. In 1935 he carried out the first deep-water trials from the research vessel ATLANTIS in the canyons from the Hudson Gorge, south. Subsequenty, two of these coring tubes were built for the Woods Hole Oceanographic Institution and were used successfully, superseding the weighted tubes which had formerly been employed. The 10-foot cores that have been obtained with this instrument by Piggot himself as well as by others fully demonstrate its superiority over anything that had previously been developed, and the cores have proved of the greatest value. Thanks are due Piggot for supervising the construction of these instruments for the Oceanographic Institution and for assistance on the first trip on which they were used.

Varney and Redwine (1936–1937) attempted to obtain additional energy by utilizing the hydrostatic pressure as a driving force, but the apparatus has not been developed beyond the experimental stage, and, as far as the authors know, a practical and satisfactory solution was not found.

Pettersson and Kullenberg (1940; 1941) have devised a coring tube in which a partial vacuum is created over the core so that the outside hydrostatic pressure will help to force the sediment into the tube and thereby also decrease its resistance to penetration. This coring tube has been used in the Swedish fiords, and penetrated up to 8.5 m in soft and 6.8 m in firm bottom. The corresponding core lengths were 8.5 and 4.2 m; the longest cores ever taken in a single drive by any method. This is particularly significant in view of the fact that the depth of the water over the firm bottom was only 25 m and the hydrostatic pressure consequently small. Details regarding the method used to force the tube into the sediment, such as weight and velocity of descent, are not given in the papers. Neither is the character of the sediment described in detail, and it is therefore difficult to compare the conditions with those along the North Atlantic coast of America.

The simplest method of obtaining additional energy without unduly increasing the weight of the sampler is to increase its downward velocity and thereby its kinetic energy. Emery and Dietz (1941), and Shepard and Emery (1941) increased velocities by allowing the winch to run on the brake for the last 300 feet of the descent. Velocities up to 20 ft./sec. and penetrations up to nearly 17 feet in soft materials

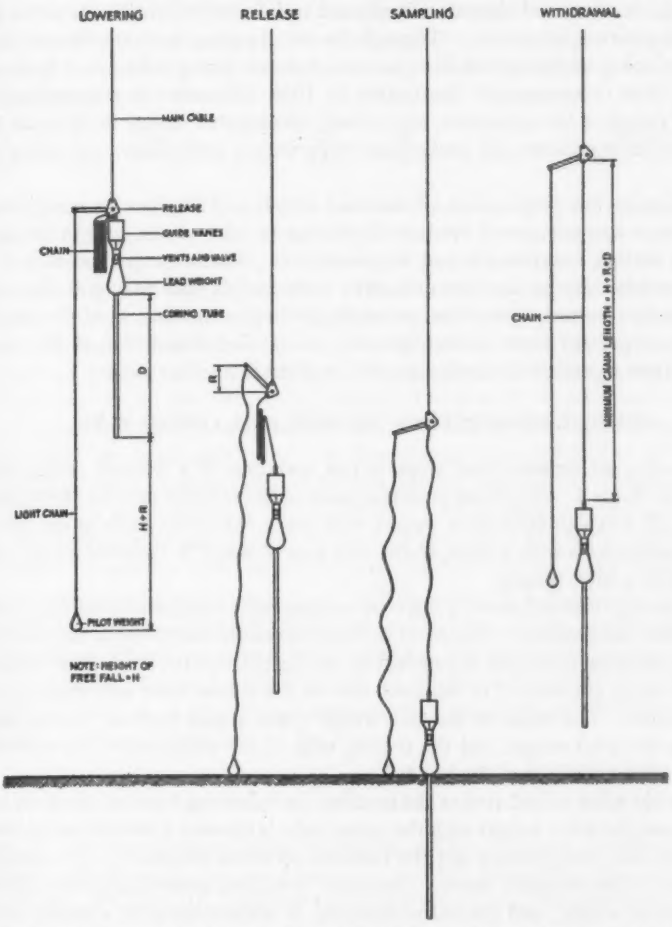

FIGURE 1.—*Principal elements and steps of operation of the free-fall coring tube*

were thereby attained, but the depth of penetration in coarse or stiff sediments was still relatively small.

The method of obtaining additional velocity by letting the winch run out on the brake alone could not be used in the case of the heavier equipment on ATLANTIS, for which the maximum safe speed at which the wire can be payed out is about 3 ft./sec. In an effort to overcome this difficulty of attaining the requisite velocities, and to develop a sampler capable of deep penetration which could be operated by crews inexperienced in the handling of explosives, the writers held many discussions of the problems involved in the design of a suitable sampler, and of the limitations which are necessarily imposed by its use on shipboard. As a result, a coring tube was developed which can be released from the main cable at a predetermined distance

above the bottom, and thereafter is allowed to fall freely through the water for the remaining part of its descent. Through the aid of a grant from the Penrose Bequest of The Geological Society of America, two free-fall coring tubes were built for the Woods Hole Oceanographic Institution in 1940. Hvorslev is responsible for the general theory of the apparatus, the authors collaborated closely in its detail design, and Stetson supervised the preliminary experiments and subsequent coring operations.

This paper was prepared in all essential details in 1941, but its completion and publication was postponed because of priority of other work, and in the hope of making further experiments and improvements. Further experiments had to be abandoned because of the war, and, since considerable time may still elapse before they can be resumed, it was thought advisable to give an account of the new coring tube in its present state of development. A detailed description of the cores obtained, from a geological standpoint, will be given in another paper.

GENERAL PRINCIPLES OF THE FREE-FALL CORING TUBE

The principal elements and steps in the operation of a free-fall coring tube are shown in Figure 1. The three principal parts of the sampler are: (1) the coring tube proper, (2) a streamlined drive weight with check valve and guide vanes, and (3) a release mechanism with a lever, to the long arm of which is attached a light cable or chain with a pilot weight.

The coring tube and drive weight are permanently attached to the base plates of the release mechanism by means of a chain, hereafter called the coring-tube chain. During lowering, this chain is bunched up and lightly secured with twine to the drive weight, which is attached to the short arm of the release lever and balanced by the pilot weight. The length of the pilot weight chain is such that the vertical distance between the pilot weight and the cutting edge of the coring tube is a little greater than the desired height of the free fall.

When the pilot weight strikes the bottom, the balancing force on the lever is eliminated, and the drive weight with the coring tube is released and falls freely, breaking the twine and straightening out the bunched up chain behind it. The assembly is kept vertical by the guide vanes. The winch is stopped immediately after the release of the drive weight, and the entire assembly is withdrawn after allowing sufficient time for the free fall and the penetration of the coring tube into the bottom sediment.

THEORETICAL CONSIDERATIONS

The force with which the coring tube strikes the bottom depends not only on its weight and downward velocity but also on the elastic properties of the sediments, and it is therefore difficult to evaluate. For the purpose of estimating the influence of the velocity, it is easier to consider the energy. The total energy, E, expended from the moment the coring tube strikes the bottom until it comes to rest after a depth of penetration, D, is the sum of the potential and kinetic energy, or:

$$E = W\left(D + \frac{v^2}{2g}\right) = W(D + h),$$

where W is the weight of the coring tube and drive weight, v its velocity at the start of the penetration, and g the acceleration of gravity. The height $h = v^2/2g$ may, borrowing a term from hydraulics, be called the velocity head. Values of h for increasing values of v are as follows:

$v =$	3	5	10	20	30	40	50	60 ft./sec.
$h =$	0.14	0.39	1.55	6.22	13.99	24.87	38.86	55.96 ft.

For the usual safe unreeling speed of 3 to 5 ft./sec., the value of h and thereby the kinetic energy constitutes only a small fraction of the potential energy, even when a penetration of only a few feet is obtained, whereas it may be several times the potential energy for large values of v. This increase in available energy with v is still more striking considering that the higher velocities also produce a greater penetration and thereby make more potential energy available. For example, when a conventional gravity-coring tube is lowered at a speed of 5 ft./sec. and penetrates 4 feet into the bottom, the total energy expended is $E = W \times 4.39$, but if by a free fall of about 30 feet the velocity is increased to 40 ft./sec. (*see* Figure 2) and a penetration of 10 feet is obtained, then the total energy expended is $E = W \times 34.87$, or more than eight times as much as for the conventional gravity-coring tube.

The problem of determining the velocities of a body freely falling through air or water was solved long ago, and the solution can be found in various textbooks and handbooks. If gravity were the only force acting upon the body, the velocity would increase according to the formula $v = \sqrt{2gH}$, where H is the height of the fall. However, the falling body meets resistance in the form of fluid friction and hydrostatic pressure differences caused by the motion; this resistance increases with the square of the velocity, and when it equals the weight of the body the maximum or terminal velocity, v_t, is reached and remains constant during any further fall. The terminal velocity is determined by the formula:

$$v_t^2 = \frac{2}{c}\frac{g}{\gamma}\frac{W}{A},$$

where c is a dimensionless coefficient called the coefficient of drag, γ is the unit weight of water or 64 lbs./cu.ft. for sea water, and A is the maximum cross-sectional area of the body. The drop, H, required to develop the velocity v is determined by:

$$H = \frac{v_t^2}{2g} \ln \frac{v_t^2}{v_t^2 - v^2},$$

and the duration of this fall by:

$$T_f = \frac{v_t}{g} \ln \left[e^{gH/v_t^2} + \sqrt{e^{2gH/v_t^2} - 1} \right]$$

In deriving these formulas it is assumed that the velocity at the start is zero; that is, the unreeling speed of the cable is not taken into consideration, but this speed is generally so small that its influence is negligible. Computation of the time required for penetration (Tp) of the coring tube is more difficult, since not only the depth of penetration but also the penetration resistance and its variation with depth

must be known, and this resistance varies with both the character and the sequence of the strata. However, the formula:

$$T_p = \frac{2D}{v}$$

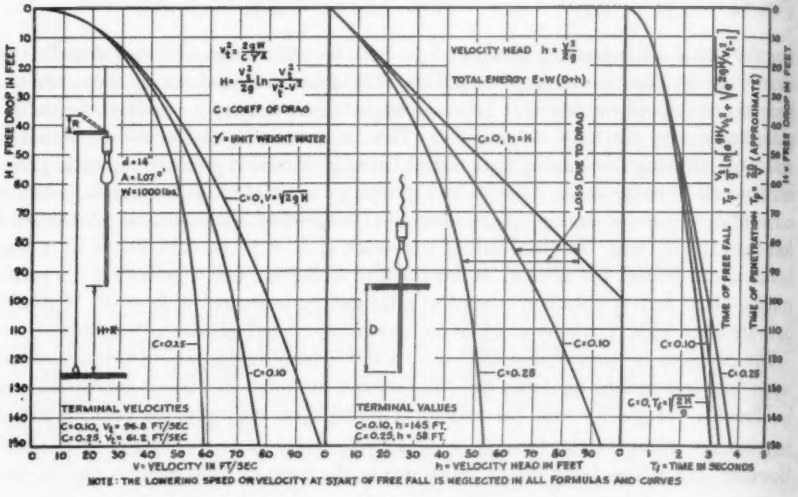
H = FREE DROP IN FEET
V = VELOCITY IN FT/SEC
h = VELOCITY HEAD IN FEET
T_f = TIME IN SECONDS
TERMINAL VELOCITIES
C=0.10, V_t = 96.8 FT/SEC
C=0.25, V_t = 61.2 FT/SEC
TERMINAL VALUES
C=0.10, h=145 FT.
C=0.25, h = 58 FT.
C=0, V=√2gH
C=0, h=H
C=0.25
C=0.10
VELOCITY HEAD h = V²/2g
TOTAL ENERGY E=W(D+h)
LOSS DUE TO DRAG
TIME OF FREE FALL
TIME OF PENETRATION
C=0, T_f = √2H/g
d=14"
A=1.07 sq ft
W=1000 lbs.
C = COEFF OF DRAG
γ = UNIT WEIGHT WATER
NOTE: THE LOWERING SPEED OR VELOCITY AT START OF FREE FALL IS NEGLECTED IN ALL FORMULAS AND CURVES

FIGURE 2.—*Velocity, energy, and duration of fall for 1000 lbs. sampler*

will give results sufficiently accurate for the purpose here and is on the safe side when D is taken as the total length of the coring tube proper.

The velocities, velocity heads, and the duration of the free fall have been computed by means of the above formulas for the coring tube built for the Woods Hole Oceanographic Institution, and are given graphically in Figure 2 as a function of the free fall, H. The weight of the coring tube and drive weight is approximately 1000 pounds, and the maximum diameter of the latter is 14 inches, corresponding to a cross-sectional area $A = 1.07$ sq. ft. The coefficient of drag has not been determined, but it was estimated to be between $c = 0.10$ and $c = 0.25$. It will be seen from these curves that the values of c has very little influence on the values of T_f within the practical range of the free drop. The influence of c on v and h is insignificant for small values of H, but it increases rapidly with H and is very great in case of the terminal values v_t and h_t.

FORCES AND DEFORMATIONS DURING CORING

Before describing the design details of the coring tube, it is desirable to review briefly what happens when the tube is forced into the sediment. Some of the principal conceptions and the photographs presented in this section are the results of experiments carried out by Hvorslev (1940a) for the Committee on Sampling and

Testing, Soil Mechanics and Foundations Division, American Society of Civil Engineers. Other experiments have also been made by Piggot (1941) and Emery and Dietz (1941).

When the coring tube is forced into the sediment, an amount of material corresponding to the volume of the walls of the coring tube and its liner is pushed aside. During the first part of the coring operation, when the friction between the core and the tube still is small, some of the displaced material may possibly be forced into the tube, thereby causing a distortion and an increase in thickness of the individual strata of the core. In experiments with fairly thick-walled coring tubes, forced slowly into soft material, an increase in thickness of more than 50 per cent for the upper strata of the core has been observed; but it was also noted that the entrance of excess material decreased to a small amount when the velocity of penetration exceeded a few feet per second. Nevertheless, it is desirable to reduce the wall thickness of the coring tube and its liner to the minimum consistent with structural requirements, not only to avoid entrance of excess material but also to decrease the resistance to penetration.

Entrance of soil into the coring tube is hindered in part by the hydrostatic pressure on top of the core and in part by the friction between the core and the walls of the liner. The hydrostatic pressure over the core is counteracted by the pressure in the pore water below the coring tube, but adequate vents must be provided to prevent any material increase in the pressure over the core as it enters the tube and expels the water. At high velocities of penetration the vents should have an area at least equal to that of the core and should also be streamlined (Piggot, 1936).

The friction between the core and the liner is transmitted to, and increases the pressure on, the material below the coring tube. The friction and pressure increase with the length of the core, and may, after a certain length of core is reached, cause considerable compaction of loose and partially saturated subaerial soils thereby shortening the core. However, it is doubtful that any material compaction will occur during coring operations on the ocean bottom. The sediments are here fully saturated, and only a negligible amount of water can be forced out of the material during the short period required for full penetration of the coring tube. On the other hand, when the increase in pressure below the coring tube reaches a certain value, it will cause a downward deflection and a consequent stretching and decrease in thickness of the strata before they enter the tube (Pl. 2, fig. 1). This downward deflection and stretching and not actual compaction is generally the factor responsible for a shortening of the core.

A moderate downward deflection and decrease in thickness of the strata before they enter the tube may occur without causing any visible distortion of the strata in the core, but, when the deflection becomes so large that it causes a reduction in thickness greater than 5 to 15 per cent, it will also produce a downward curvature of the strata (Pl. 4, fig. 2). The inside friction may in certain cases reverse this curvature close to the cylindrical surface of the core. An upward curvature of the strata over the entire cross section is occasionally observed in the upper part of a core. Such a curvature may be caused either by the inside friction or by entrance of excess material and a consequent increase in thickness of the particular strata.

In brittle materials the increase in pressure below the tube may cause shear failures and abrupt displacements (Pl. 4, fig. 3 *upper part*,) instead of a uniform deflection and decrease in thickness. It should be noted that some relatively soft materials act like a brittle substance when subject to sudden stress changes and deformations. In sediments consisting of thin strata of varying firmness, the softer strata will often be subject to a greater decrease in thickness than the firm strata (Pratje, 1934; 1936). When the deformations become large, the major part of the soft strata may be pushed aside while the firm strata are broken up and mixed with the remnants of the soft strata (Pl. 4, fig. 3, lower part). The core will ultimately reach such a length that the corresponding inside friction prevents further entrance of material. A bulb or cone of sediment is then formed below the cutting edge (Pl. 2, fig. 2), and further penetration merely results in pushing the sediment aside as a solid bar would do.

To obtain long and relatively undisturbed cores, the inside friction must be reduced. This is accomplished (1) by keeping the inside surface of the liner absolutely smooth and clean (pitted and corroded tubes should not be used), and (2) by making the diameter of the cutting edge, D_c, slightly smaller than the inside diameter, D_s, of the liner, so that a small inside clearance, $(D_s - D_c)$, is produced. The inside clearance should, normally, be only large enough to compensate for the elastic expansion of the core as it enters the tube. If it is larger than that, the core will be deprived of lateral support; in stiff material this may again cause elimination of the inside friction and loss of the core during the withdrawal unless a core catcher is provided. Experiments on land have shown that an inside clearance in excess of 1.5 to 2.0 per cent of D_s often will cause loss of the core.

When an excessive inside clearance is used in soft or cohesionless materials, the core will slump and expand laterally until it is restrained by the liner, and the inside friction will then be re-established. Slumping may cause disturbance of the structure and a decrease in strength of the material; it cannot be permitted when undisturbed samples are desired, but it will not seriously impair the value of cores taken solely for geological examination. The larger inside clearance will unquestionably help to produce longer cores and has been used successfully in many instances, especially when a core catcher also is provided. However, a lateral expansion, in excess of a purely elastic one, will cause a shortening of the core. If the inside clearance is $(D_s - D_c) = m D_c$, and it is assumed that there is no volume change of the material, then the shortening of the core length, $m L$, is given by

$$m = 2n - n^2,$$

or roughly twice the inside clearance when the latter is small. Clearances up to 10 per cent have been used in some coring tubes and may, disregarding volume changes, cause a shortening of the core up to 19 per cent. To the shortening caused by slumping of the core must be added the effect of a possible downward deflection, stretching, and reduction in thickness of the strata before they enter the coring tube.

The above-mentioned causes of shortening of the core in certain materials may be counteracted by a liberation and expansion of gases dissolved in the pore water. At the hydrostatic pressure existing at great depths considerable amounts of various

gases may be dissolved in the pore water, especially in sediments containing organic materials, or where the ground-water flow has passed through such deposits. When the core is brought to the surface, the hydrostatic pressure is reduced to, and, on account of capillary action, even below atmospheric pressure. The dissolved gases are then partially liberated and expand, thereby increasing the length of the core. An increase in length after recovery amounting to several per cent has been observed for cores taken at such shallow depths as 25 to 50 feet in New York Harbor. The liberation of gases takes place rather slowly and may continue for a considerable period of time after the core is brought to the surface. It is therefore advisable to measure the core length accurately immediately after the coring tube is brought to the surface, in order to be able to determine the amount of any subsequent expansion caused by liberation or gases, or any shrinkage caused by drying.

CONSTRUCTION DETAILS

GENERAL STATEMENT

The detail design of the sampler was to a large extent governed by available materials and equipment. Because of some uncertainty with respect to the energy required to penetrate the very stiff bottom sediments of the Atlantic continental slope, and also because of some doubt with regard to the vertical stability of the sampler during the free fall, it was decided to make the drive weight as heavy as possible, considering the strength of the wire and the capacity of the winch on ATLANTIS.

CORING TUBE

The coring tube proper (Pl. 1) consists of a section of seamless steel tubing, reamed to an internal diameter of 2.200 inches to provide a sliding fit for a liner of brass tubing 10 feet 00 inches long, with an outside diameter of 2.000 inches and a wall thickness of 0.025 inch. The upper half of the steel tubing has an outside diameter of 2.500 inches; the diameter of the lower half is gradually decreased to 2.200 inches, which dimension is maintained for the lower 2 feet of the tube. It was hoped that this reduction in the outside diameter, besides lessening the danger of excess material entering, would increase the depth of penetration, at least into deeper-lying, firm strata. It would have been desirable to maintain the smaller outside diameter over the entire length of the tube, and the use of a tube with a uniform outside diameter of 2.250 inches was considered. However, it might not have had sufficient strength to withstand the bending moments to which it would be subjected during the withdrawal, in case the ship drifts during the coring operation, thereby causing considerable wire angle.

Close to the cutting edge, the outside diameter is again increased slightly so that it will provide a small outside clearance and reduce the friction between the lower part of the tube and the surrounding material. The consequent increase in wall thickness is also desirable to counteract the weakening effect of the threads for the cutter. The increased diameter of the bulb undoubtedly does decrease the outside friction, but it also increases the end resistance and should, therefore, be small when

the tube is to be used in stiff materials, and perhaps entirely eliminated in dense, cohesionless sediments.

Screwed into the lower end of the tube is a sharp, hardened cutter with an inside diameter slightly smaller than that of the liner. Three interchangeable cutters, producing inside clearances of 1.0, 1.5, and 2.0 per cent, are provided.

DRIVE WEIGHT WITH CHECK VALVE AND GUIDE VANES

The upper end of the coring tube screws into a flange with another section of 2.5-inch tubing which supports the streamlined lead weights (Pl. 1; Pl. 3, figs. 1, 2). These weights were cast in sections for ease of handling. Above the weights is a short length of 5-inch standard pipe which serves as a connection to the guide vanes and as a housing for the check valve. This valve is intended to reduce the hydrostatic pressure over the core during the withdrawal, and it is streamlined in order to offer the least possible resistance to the water forced out of the tube during its penetration into the bottom. Vents in the valve housing provide easy access for inspection and cleaning.

Above the valve housing are four guide vanes, welded to a section of 2-inch standard pipe and to an encasing thin, steel cylinder. The latter protects the vanes during handling of the sampler, decreases the danger of fouling the trawl wire and chain, confines the slipstream, and increases the efficiency of the vanes. The eye bolt over he vanes was, in actual construction, replaced by a U-bolt welded to the 2-inch pipe. Several other minor changes and simplifications of the original design (Pl. 1) were made, and, when another sampler is to be built, both the drive weight and the guide vanes will probably be smaller. The total weight of the present drive weight with appurtenances and coring tube is approximately 1000 pounds.

RELEASE MECHANISM

The release mechanism consists of two roughly triangular base plates with stay bolts, spacers, and chain links, and with a bolt and bronze bushing which serves as a fulcrum for a lever with two unequal arms (Fig. 3). The drive weight with the coring tube is attached to the short arm, and a 100-pound pilot weight to the long arm of the lever. The lever arms are 1.5 and 30.0 inches long, or a ratio of 1 to 20. This means that a 2000-pound pull on the short arm is required to trip the lever, or approximately a factor of safety of two against an accidental release of the sampler. This factor of safety was considered sufficient to take care of a temporary decrease in the pull of the pilot weight, which may be caused by a sudden increase in the rate of descent during a heavy roll of the ship. Furthermore, the pilot weight is semi-streamlined to decrease the effect of such a change in the rate of descent. A safety pin through the base plates and the lever, locks the latter in position while the apparatus is being rigged and put over the side of the ship.

The sampler is attached to the base plates of the release mechanism by a $\frac{7}{16}$-inch chain so that it can be withdrawn from the bottom after the completion of coring. During lowering, this length of chain is bunched up and secured by light twine. Chain instead of wire was chosen for this purpose since wire must be coiled and

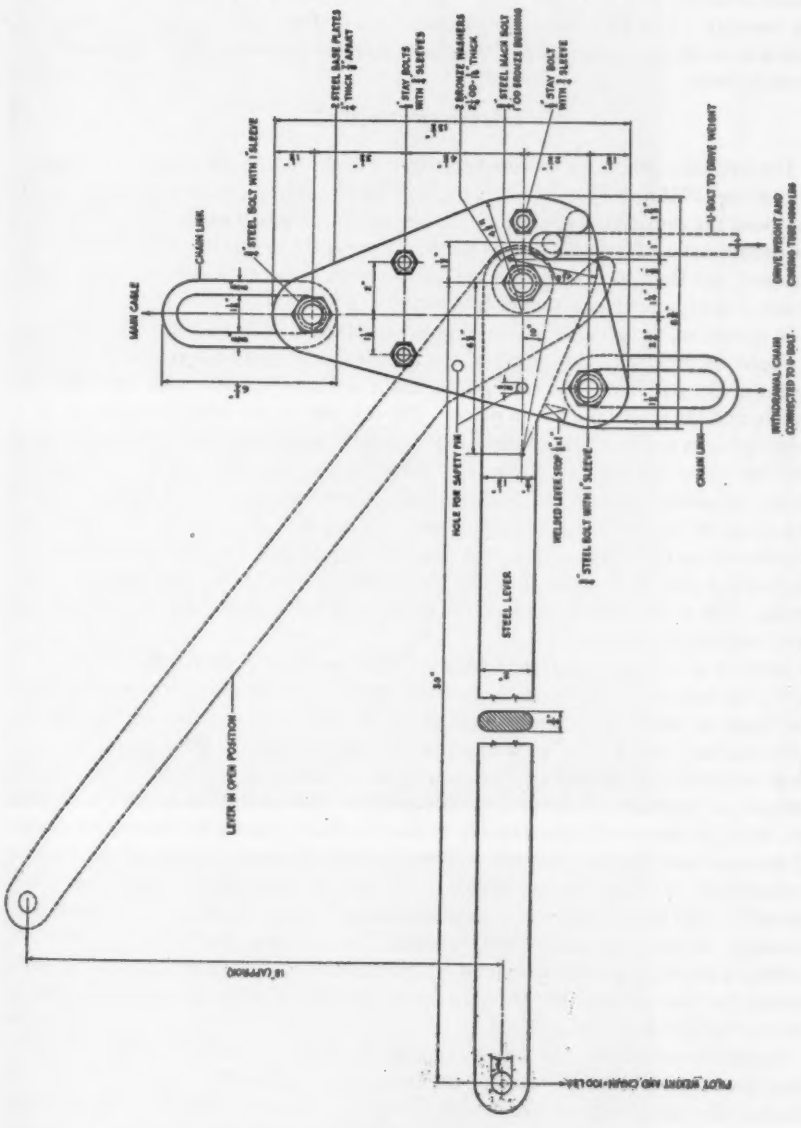
MAIN CABLE
CHAIN LINK
STEEL BOLT WITH ½" SLEEVE
2 STEEL BAR PLATES ½" THICK 4" APART
½" STAY BOLTS WITH ½" SLEEVES
2 BRONZE WASHERS 2½" OD × ½" THICK
½" STEEL MACH BOLT (OD BRONZE BUSHING
½" STAY BOLT WITH ½" SLEEVE
1½" BOLT TO DRIVE WEIGHT
DRIVE WEIGHT AND CORING TUBE 4000 LBS
WITHDRAWAL CHAIN CONNECTED TO ½" BOLT
CHAIN LINK
HOLE FOR SAFETY PIN
WELDED LEVER STOP
½" STEEL BOLT WITH ½" SLEEVE
STEEL LEVER
LEVER IN OPEN POSITION
18' (APPROX)
PILOT WEIGHT AND CHAIN 100 LBS.

FIGURE 3.—*Release mechanism for free-fall sampler*

would certainly foul and kink when rapidly straightened out during the free fall of the sampler. The light wire, by means of which the pilot weight was originally attached to the lever (Pl. 3, fig. 1) was later, and for the same reason, replaced by a $\frac{3}{16}$-inch chain.

CORING OPERATIONS

The free-fall coring tube was used on two trips with ATLANTIS during the summers of 1940 and 1941 and a total of 21 cores were taken. Coring operations were carried out along the continental slope from Hudson to Washington canyons and in the deep area southeast of the tip of Georges Bank. The depths varied from 100 to over 2250 fathoms, and the types of bottom sediments ranged from very stiff, silty clays with lenses of sand, gravel, and stones, to plastic clays.

In operation, the sampler is very simple and positive in its action. The assembly is rigged on deck with the length of the pilot-weight chain adjusted to the desired height of the free fall. The coring-tube chain is flaked down on deck and tied in a bunch, and the safety pin put in place. The sampler is then lifted horizontally on a hoisting boom and swung over the side by a wire sling spliced around the coring tube and the valve housing (Pl. 3, fig. 2). When suspended vertically from the trawl boom, the safety pin is pulled, and the sampler lowered away at the normal paying-out speed of the winch. When the moment of release and the start of the free fall is indicated on the dynamometer, the winch is stopped, and the withdrawal operation started at a very slow speed, after allowing sufficient time for the drop and the actual coring. On arrival at the surface the sampler is again picked up on the hoisting boom and swung aboard.

Because of wire angle it is very difficult, when working in deep water, to estimate how close any gear may be to the bottom, even when the amount of wire out and the depth of water is known. When excess wire is paid out after the bottom has been reached, it will lie in coils and tend to tangle and kink when taken in. The clear indication of the moment of release, which occurs in the case of the free-fall sampler, is, therefore, of the greatest advantage. The movement of the dynamometer, which is sharp and unmistakable, is due to a wave, caused by the sudden release of tension, travelling up the wire. The comparatively heavy weight of the sampler undoubtedly is a contributing factor. The moment of release was as clearly observed in 2200 fathoms as in 100, and, because of the conditions outlined above, presumably will be observed in 5000 fathoms. In contrast, the tension in the wire holding a standard gravity coring tube is decreased gradually while the tube is being driven into the bottom, and, in deep water, it is often difficult to determine when the coring operation is completed.

A possible rotation of the sampler during lowering was considered, thereby wrapping the pilot-weight chain around the sampler and preventing a proper release, or causing the coring tube to hit the pilot weight. However, difficulties of this kind were not encountered during any of the coring operations, nor did the roll of the ship ever cause a premature release. On one occasion, when a clutch failed, and the unreeling speed of the winch became too great, an accidental release occurred when the winch had to be brought up short on the brake. It only resulted in a heavy jar,

FIGURE 1. VERTICAL SECTION OF BORE HOLE
Showing start of downward deflection and stretching of soil layers below the bottom.

A B

FIGURE 2. SECTION OF BORE HOLE AND LOWER PART OF SAMPLE
Showing formation of bulb or cone-shaped plug of sediment. A — Slow penetration. B — Fast penetration.

EXPERIMENTAL SAMPLING IN VARVED CLAY

FIGURE 1. FREE FALL CORING TUBE READY FOR LOWERING.
Photo By F. B. Phleger

FIGURE 2. FREE FALL CORING TUBE BEING LIFTED ON BOARD AFTER CORING.
Photo By F. B. Phleger

HANDLING THE CORING TUBE ON SHIPBOARD

because of the cushioning effect of 2000 feet of wire which happened to be out at the time. Had it occurred with only a short length out, the wire might have parted.

RESULTS

Free drops of 7 to 10 feet were used, and, except in a very stiff and silty clay, sufficient energy was developed to force the 10-foot tube and a part of the drive weight into the sediment. Once the entire sampler was forced below the sea bottom. It is therefore evident that the available energy is sufficient to drive still longer coring tubes into the sediment for their full length, and more energy can be obtained by increasing the height of the free drop. Coring tubes with a length of 15 or 20 feet will be used in future operations. The stratification in all the cores was practically horizontal, which indicates that the sampler maintained its vertical position during the free fall.

A cutter with 2 per cent inside clearance was used in the first coring operation, and the entire core was lost. Cutters with 1 per cent inside clearance were employed on all subsequent stations. Even with this clearance the lower parts of three cores were lost during the withdrawal. In two cases this loss occurred when the coring tube was raised above the water, and possibly the check valve was not fully effective, since the rubber gasket had been damaged and a machined metal seat was used instead. Replacement of the metal plunger with a rubber or rubber-covered plunger, and other changes in the check valve, are contemplated, but its streamlined form will be maintained.

The length of the cores obtained varied from 28 to 113 inches, and a diagram of one of the longer cores is shown in Figure 4. The core contains strata of stiff clay, sand, gravel, and two large pebbles. A photograph of the boundary between a gravel and a stiff clay layer is shown (Pl. 4, fig. 1). The clay sections of the core have shrunk about 20 per cent, since it was allowed to dry approximately to the shrinkage limit in order to increase the color difference between the various materials. The climatic data based on the Foraminifera were furnished by Dr. Fred B Phleger. The original length of some of the cores may have been greater, and the entire core may have moved downwards in the tube during the withdrawal. However, the strata in the lower part of some of the cores show a distinct downward curvature (Pl. 4, fig. 2), and it is evident that the inside friction was great enough to cause a downward deflection, stretching, and reduction in thickness of these strata before they entered the tube. In the lower part of another core (Pl. 4, fig. 3) distinct shear planes are visible, and below these the sand strata are broken up and partially mixed with the remnants of the softer clay strata, the major part of which had been squeezed out. In one case a soil cone, similar to the one shown (Pl. 2, fig. 2) projected below the cutter, indicating that the limiting core length for the particular material, diameter, and inside clearance had been reached. As a whole, the length of the cores agrees fairly well with the lengths obtained in coring operations on land in similar materials, and with a tube having the same inside diameter and clearance. The cores (Pl. 4, figs. 1, 2, 3) are shown in the brass liners, which were halved longitudinally according to the method first devised by Piggot (1936).

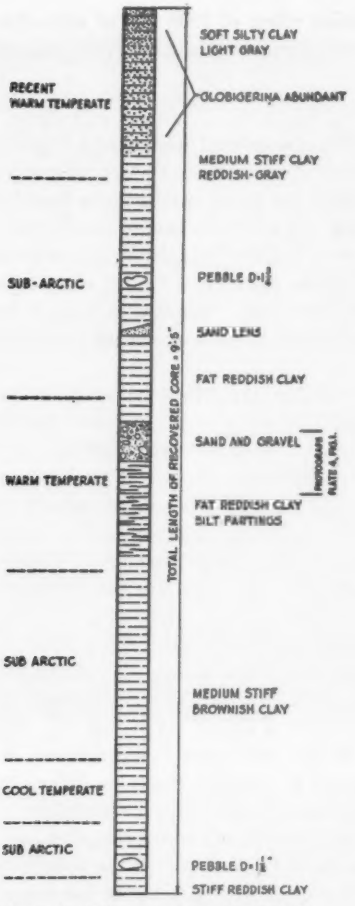

FIGURE 4.—*Diagram of core No. 9-1941*

N. lat. 40° 41', W. long. 64° 55', depth, 2250 fathoms. Climatic data from foraminifera identified by F. B Phleger

Undoubtedly much longer cores can be obtained by using a larger inside clearance. In addition, the brass liners will be replaced by newly developed, thin-walled, plastic tubing, which is transparent, easier to cut, and has a much smaller coefficient of friction than brass. An increase of the inside diameter of the coring tube will likewise permit the taking of longer cores, and sufficient energy is available to force the larger tubes into the sediment. However, these changes will increase the danger of losing the sample during the withdrawal, and it may become necessary to use a core catcher. A simple and efficient type has been developed by Emery and Dietz (1941).

FIGURE 1. SECTION OF CORE NO. 9-1941
Showing layers of gravel and firm red clay. N. Lat. 40° 41′, W. Long. 64° 55′, depth 4120 meters.

FIGURE 2. BOTTOM SECTION OF CORE NO. 1-1941
Showing downward curvature of very stiff, silty clay strata. N. Lat. 40° 10′, W. Long. 68° 30′, depth 550 meters.

FIGURE 3. LOWER SECTION OF CORE NO. 7-1941
With thin layers of sand, silt and reddish clay. Top, shear planes and displacement. Bottom, distortion, breaking up and mixing of layers with clay partially squeezed out. N. Lat. 40° 34′ W. Long. 65° 02′, depth 4150 meters.

EFFECT OF CORING TUBE ON DIFFERENT TYPES OF BOTTOM

RESUMÉ

The practical tests with the free-fall coring tube have demonstrated that the proposed method of increasing the available energy of a gravity-coring tube is entirely feasible. The apparatus is simple in construction and easy, flexible, and reliable in operation. The method is independent of the design of the coring tube proper, and the proposed apparatus can be used without change at any ocean depth.

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FORAMINIFERA OF TWO SUBMARINE CORES FROM THE NORTH ATLANTIC BASIN

BY FRED B PHLEGER, JR. AND WALTER A. HAMILTON

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ABSTRACT

The Foraminifera of two submarine cores from the basin of the western North Atlantic have been examined. Vertical faunal variations suggest two sub-Arctic faunas separated by a warm-temperature fauna, and these are beneath the present warm-temperate fauna. The Arctic faunas are interpreted as representing the two latesst ubstages of the Wisconsin. A post-Wisconsin fauna in one core suggests warmer surface waters than at present.

Continuous sampling and quantitative study of the faunas are the most feasible methods for study of core faunas. A method of studying sizes of Foraminifera is described, and a possible correlation between sizes and ecologic factors is indicated.

INTRODUCTION

Foraminifera of two submarine cores from the western North Atlantic have been studied quantitatively to determine the frequency and size distribution of each species. The purpose of this study is: (1) to determine the environmental changes represented by the core Foraminifera in this area; (2) to examine the cores by a continuous sampling method in order to note detailed vertical changes of the faunas in the cores and determine the value of continuous sampling as compared with other methods; (3) to study size distribution, its variation in the cores, and its possible application to studies of core Foraminifera.

LOCATION OF THE CORES

The two cores studied are from a series of nine cores obtained by H. C. Stetson and the authors during the summer of 1941 from the research ship ATLANTIS, belonging to the Woods Hole Oceanographic Institution. They were taken south of the eastern end of Georges Bank, from near the edge of the Atlantic basin at that place. The locations and depths are as follows:

Core	*N. Lat.*	*W. Long.*	*Depth*	*Length of Core*
7-41	40° 34′	65° 02′	4150 m	188 cm
9-41	40° 41′	64° 55′	4120 m	286.7 cm

METHOD OF STUDY

The samples for Foraminifera were taken continuously in the cores so that the entire length of the core was sampled. Positions of some of the samples were determined by the layering of the sediment, but where the sediment appeared to be uniform a sample approximately 5 cm. long was taken. This detailed sampling gives an accurate check on any slight vertical faunal variations which may be present. The positions of the samples in the cores are shown in Table 1.

The Foraminifera in some of the large samples were floated with carbon tetrachloride. Most samples, however, were examined without flotation to prevent the loss of specimens which are not freed by flotation.

The quantitative system of examination and study of the Foraminifera used on these cores follows that described by Phleger (1942, p. 1078). The percentage calculations are based on a 200-per cent system in which the total pelagic specimens equal 100 per cent in each sample, and the benthonic specimens equal 100 per cent. This makes it possible to consider the pelagic and benthonic groups separately, and it does not interfere with studying the total sample. In counting for species frequency only a small percentage of large samples was counted; however, the total number of specimens in each sample was either counted or estimated, and these data are listed in Table 2.

A size study of the species has been attempted. Each species was arbitrarily divided into five size groups into which the specimens appeared to group themselves. Since sizes of different species vary, size groups must be set up for each species. There are large variations in absolute size between the species in this fauna. *Globoro-*

TABLE 1.—*Positions of the samples in the cores*

Core 7–41		Core 9–41	
Sample	Centimeters	Sample	Centimeters
1	0 – 3	1	0 – 5
2	3 – 10	2	5 – 10
3	10 – 16	3	10 – 15
4	16 – 23	4	15 – 20
5	23 – 30	5	20 – 25
6	30 – 35	6	25 – 30
7	35 – 41	7	30 – 35
8	41 – 45	8	35 – 40
9	45 – 50	9	40 – 45
10	50 – 55	10	45 – 50
11	55 – 60	11	50 – 55
12	60 – 65	12	55 – 60
13	65 – 70	13	60 – 65
14	70 – 75	14	65 – 70
15	75 – 80	15	70 – 75
16	80 – 85	16	75 –80
17	85 – 90	17	80 – 85
18	90 – 95	18	85 – 90
19	95 –100	19	90 – 95
20	100 –105	20	95 –100
21	105 –110	21	100 –105
22	110 –115	22	105 –110
23	115 –120	23	110 –115
24	120 –124	24	115 –120
25	124 –128	25	120 –124.5
26	128 –131	26	124.5–128.5
27	131 –134.5	27	128.5–139
28	134.5–136.5	28	139 –145
29	136.5–140.5	29	145 –150
30	140.5–144	30	150 –155
31	144 –146	31	155 –160
32	146 –150	32	160 –165
33	150 –155	33	165 –170
34	155 –157	34	170 –175
35	157 –159.5	35	175 –180
36	159.5–161.5	36	180 –185
37	161.5–163.5	37	185 –190
38	163.5–164.5	38	190 –195
39	164.5–166	39	195 –200
40	166 –171.5	40	200 –205
41	171.5–174	41	205 –210
42	174 –180	42	210 –215
43	180 –186.5	43	215 –220
		44	220 –225
		45	225 –230
		46	230 –235
		47	235 –240
		48	240 –245
		49	245 –250
		50	250 –255
		51	255 –260
		52	260 –265
		53	265 –270
		54	270 –275
		55	275 –278

TABLE 2.—*Approximate number of specimens per sample*

Core 7-41		Core 9-41	
Sample	Number of specimens	Sample	Number of specimens
1	8250	1	3690
2	2940	2	13780
3	404	3	23100
4	1970	4	23600
5	3080	5	
6	700	6	3140
7	428	7	10240
8	494	8	13000
9	576	9	4700
10	664	10	12350
11	1150	11	9500
12	704	12	5300
13	2320	13	1820
14	958	14	26
15	274	15	126
16	171	16	5
17	410	17	64
18	264	18	216
19	154	19	324
20	212	20	453
21	350	21	474
22	437	22	727
23	343	23	834
24	221	24	205
25		25	1240
26	26	26	
27	26	27	193
28	19	28	776
29	88	29	283
30	62	30	231
31	19	31	204
32	95	32	433
33	52	33	161
34	16	34	430
35	15	35	516
36	28	36	394
37	38	37	99
38	30	38	594
39	24	39	85
40	258	40	258
41	180	41	640
42	106	42	1600
43	290	43	1080
		44	5120
		45	8230
		46	1050
		47	612
		48	1380
		49	2720
		50	2810
		51	886
		52	3
		53	0
		54	3
		55	0

TABLE 3.—*Sizes of species*
(In millimeters)

Species	Size groups				
	I	II	III	IV	V
Globigerina bulloides	.30	.50	—	—	—
G. inflata	.45	.65	.75	1.00	1.20
G. pachyderma	.25	.35	.50	—	—
G. dubia	.55	.65	.85	1.05	1.25
Globigerinoides rubra	.50	.60	.75	.85	
Globoratalia menardii	1.15	1.30	1.50	1.60	1.90
Uvigerina peregrina	1.10	1.35	1.90		
Elphidium incertum	.30	.50	—	—	—
Cibicides sp. 1	.30	.50	.70	—	—
Virgulina sp. 1	.55	.75	.85	—	—

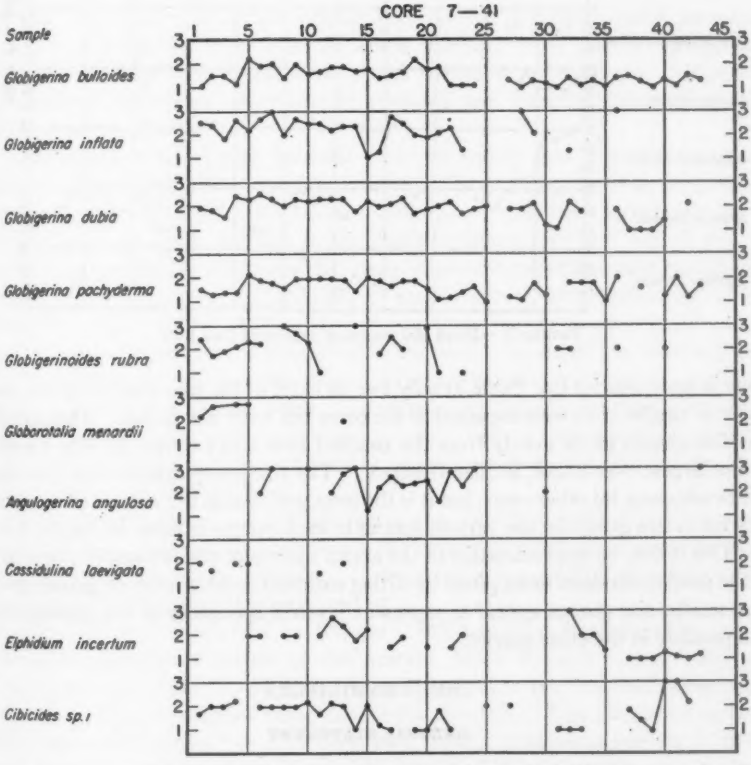


FIGURE 1.—*Mean size groups of species in Core 7-41*

talia menardii, for example, in its smallest size group (Group I) is larger than the largest size group of either *Globigerina inflata* or *Globigerinoides rubra*.

The size in millimeters for each of the size groups identified for 10 of the most important species in the cores is given in Table 3. The sizes and size groups have been set up on an arbitrary basis utilizing past experience in approximate sizes of species likely to occur, and a reference slide of sizes was made up for each species.

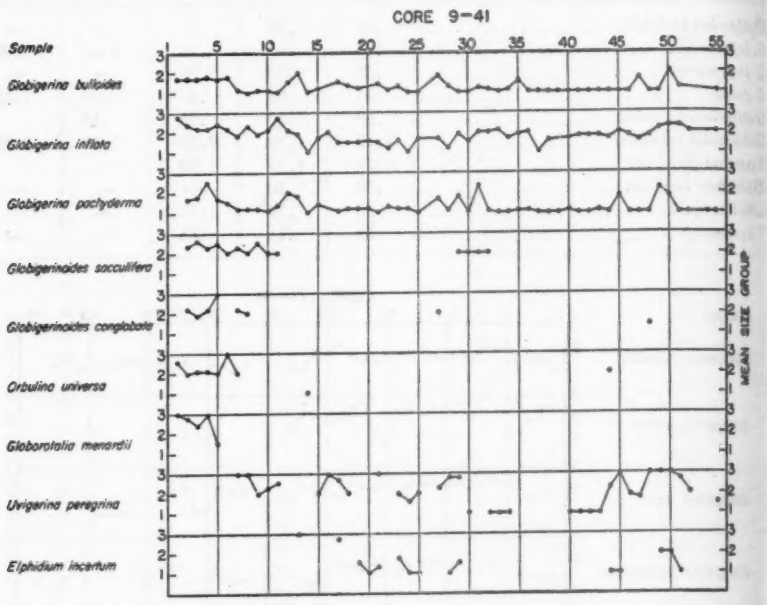


FIGURE 2.—*Mean size groups of species in Core 9-41*

Thus in some species (*see* Table 3) only two or three of the five sizes are given since larger or smaller sizes were expected in the cores but were not found. Theoretically the sizes should grade evenly from the smallest ever encountered, in Size Group I to the largest ever found, in Size Group V. The size-group system here used may not be adequate for other areas, but it is the most practicable the writers could devise. The mean size group for the various species in each sample is listed in Figures 1 and 2. This is only an approximation of the actual mean size and is roughly comparable to the median diameter determined by sifting sediments with a series of graded sieves. The smaller size groups appear to represent juvenile specimens in the globigerinids, and possibly in the other species.

THE FORAMINIFERA

GENERAL STATEMENT

Species listed in Plate 1 are the most common and important ones in the samples studied. Conclusions concerning water temperature during the length of time represented by the cores can be made mainly from the percentage-occurrence data listed

in Plate 1. Some of the rare species were not used because they are difficult to identify and are of little quantitative significance, but these constitute less than 1 per cent of the specimens in any sample. Only species which could be given consistent identifications have been used as important indicators of environmental conditions. Most of the species in the present faunas are illustrated by Phleger (1939, Pls. 1–3).

DISTRIBUTION OF CERTAIN FORAMINIFERA

Certain faunas of Foraminifera are limited in distribution at the present time to either tropical, subtropical, temperate, sub-Arctic, or Arctic waters. When occurrences of faunas like those at present living in regions limited by certain temperatures are found below the surface sediments, these older faunas are considered to be of the same temperature range as their modern counterparts. The great majority of the samples were composed almost entirely of pelagic types; the top samples from the cores are essentially a *Globigerina* ooze.

Present distribution of certain species important in this study which have been recorded previously by other investigators is partially listed below. Phleger and others have referred to distribution of certain species in general terms; this present list constitutes somewhat more specific regional, and therefore temperature, distribution of the species.

Identification of *Globigerina bulloides* varies so widely that distribution records may contain several related species; universal distribution, however, is possible. Herron-Allen and Earland (1932) report common to abundant occurrences of *G. bulloides* from the South Atlantic in the Falkland Island area and that of the adjacent seas. Earland (1934) adds that most of these occurrences were outside the Antarctic convergence line, and thus largely excluded from the coldest waters of the Antarctic. Schott (1935) records *G. bulloides* from the equatorial water of the Atlantic but points out that the occurrences are most common in the relatively cool New Guinea Current. *G. bulloides* appears to be an indicator of relatively cool water but not necessarily of Arctic water. Occurrences in tropical or even subtropical water should be checked with cold-current charts. Lack of consistent identification on the part of several workers and paucity of accurate frequency-distribution data prevent this at the present time.

Globigerina dubia is recorded by Cushman as abundant in samples from the western North Atlantic. Some of the specimens in the present samples which were identified as *G. dubia* may belong to *G. bulloides*. *G. dubia* appears to be of dominantly warm-temperate distribution, but this is not certain.

Globigerina inflata is reported by Phleger (1939) as common to abundant in the modern warm-temperate waters of the western North Atlantic Ocean. Herron-Allen and Earland (1932) record *G. inflata* as abundant in the Falkland Island area and as being the most common pelagic species in this area. This area has a surface-temperature range from 4° to 8°C. (Sverdrup, 1942). Chapman and Parr (1937) report this as a common species in the cool waters south of Australia, and Earland (1933; 1934) finds it common in the South Georgia region and elsewhere on the edge of the Antarctic Ocean. From these occurrences *G. inflata* seems to be a warm-

temperate to cool-temperate type. Its distribution appears most common in areas having an intermediate temperature. The present writers interpret *G. inflata* as primarily warm-temperate in distribution.

Chapman and Parr (1937) report that *Globigerina pachyderma* is very common in the Antarctic Ocean south of Australia. This is corroborated by reports of Herron-Allen and Earland (1932) and Earland (1933; 1934) who indicate that it is universally distributed in the Falkland Island area and that it is the most abundant globigerinid in the Antarctic. *G. pachyderma* appears to be largely Arctic (or Antarctic) to sub-Arctic in range and should indicate cold water if it occurs with a high frequency to the exclusion of most other pelagic types. The present writers find it difficult to explain the rather high percentage of *G. pachyderma* in many of our warm-water samples. There are two possible explanations: Either (1) identification of this species has not been consistent, or (2) there is a mixture of cold- and warm-water pelagic types in this region on the northern margin of the Gulf Stream.

Globigerinoides conglobata is widely distributed in the tropical waters around the Philippine Islands (Cushman, 1921). It is extremely abundant in the warm-temperate regions of the Atlantic according to Cushman (1920–1931), and Phleger (1939) reports it as common to abundant in many warm-temperate samples from the western North Atlantic. Earland (1933) reports two occurrences in the Antarctic near South Georgia, and these seem to be the only occurrences of this species known in the Antarctic. *G. conglobata* is tropical to warm temperate in distribution.

Globigerina rubra is recorded by Cushman (1920–1931) as abundant in the warm-temperate waters of the western North Atlantic. Cushman (1921) reports rare occurrences of this species in the tropical waters of the Pacific region. Herron-Allen and Earland (1932) and Earland (1933) report a few occurrences in the Antarctic. This species was the most abundant found in the plankton tows taken near the outer edge of the Gulf Stream in the North Atlantic by Phleger (1945). *G. rubra* seems to be a warm-temperate species and in abundance may be particularly characteristic of Gulf Stream and Sargasso Sea water.

Globigerinoides sacculifera is recorded by Cushman (1921) as very abundant in the tropical regions of the Pacific. Phleger (1939; 1942) and Cushman (1920–1931) report it as common to abundant in the warm-temperate regions of the Atlantic. One specimen was recorded on the Australasian Antarctic Expedition (Chapman and Parr, 1937). *G. sacculifera* is a tropical to warm-temperate species.

Globorotalia menardii is reported as common in the tropical Pacific waters (Cushman, 1921). It is abundant in the warm-temperate regions of the North Atlantic (Cushman, 1920–1931; Phleger, 1939; 1942); Schott (1935) reports this species abundant in his tropical Atlantic stations. Four specimens are reported by Herron-Allen and Earland (1932) and Earland (1934) from the Antarctic. This is a tropical to subtropical species.

Cassidulina laevigata is reported by Miss Frances Parker (personal communication) as very common in the shallow coastal waters of the western North Atlantic. Cushman (1921) found it rare in the tropical waters of the Pacific. Cushman (1920) reports this species rare in the Arctic, while Herron-Allen and Earland (1932) record widespread occurrences in the Antarctic. It is probably a cool-temperate or coastal species.

Elphidium incertum is reported by Miss Parker (personal communication) and Cushman (1920–1931) as common in the western North Atlantic. Cushman (1920) reports it from the Arctic and Herron-Allen and Earland (1932) and Earland (1933; 1934) record it from the Antarctic. It is probably cool-temperate in range.

CORE FAUNAS

CORE 7-41

Samples 1–5 contain the upper warm-water fauna. *Globigerina inflata* constitutes a large percentage of the fauna, and this is the only stage in which *Globigerina menardii* shows any significant occurrence. All of the other warm-water species are present in quantity, and *Globigerina pachyderma* is of relatively low frequency.

Samples 6–15 contain the upper cold-water fauna. All of the warm-water indicators are absent except for a relatively low frequency of *Globigerina inflata* which continues throughout this stage. *Globigerina pachyderma* begins its increased frequency in sample 6 and constitutes more than 50 per cent of the pelagic group throughout this stage. Occasional occurrences of warm-water species are present in this stage but never constitute over 1 per cent of the pelagic group present in any one sample.

Samples 17–23 contain a middle fauna which is variable but is of a warmer-water aspect than the cold zone above; it indicates cooler-water conditions than is evidenced by the fauna at the top of the core. The occurrences of *Globorotalia truncatulinoides* and the sudden decrease of *Globigerina pachyderma* in sample 17 mark the upper boundary of this stage. Samples 24–29 also may be a part of this stage.

Samples 30–43 contain the lower cold-water fauna. *Globigerina inflata* occurs less frequently in this stage in the core than in any other. *Globigerina pachyderma* increases in sample 30 and remains prominent. A cool rather than cold-water stage is evident in samples 37–40 where there are two occurrences of *G. rubra* and there is a decrease in *G. pachyderma*. Sample 43 shows a marked decrease in *G. pachyderma* suggesting a warmer stage not far below the section of sediment contained in this core.

CORE 9-41

Samples 1–7 contain the upper warm-water fauna with a warm-water maximum below sample 1. The first sample contains only three definite warm indicators. *Globorotalia menardii* increases its frequency in sample 2, then drops almost steadily and is absent from sample 6. Samples 2–6 contain six warm-water species. Sample 7 shows a sharp change in the major pelagic species from *Globigerina inflata* to *G. bulloides* but still contains four warm-water species. Samples 7–11 appear to be transitional between cold and warm water.

Samples 8–26 contain the upper cold-water fauna with no clearly defined upper and lower boundaries. From sample 21 to the bottom of this stage there are minor occurrences of warm-water species, none of which counterbalance the high percentages of *G. pachyderma* and *G. bulloides*.

Samples 27–32 contain a middle warm-water fauna which may represent somewhat cooler-water conditions than the present-day fauna.

Samples 33–35 are intermediate.

Samples 36–55 contain a cool- to cold-water fauna. Infrequent occurrence of some warm-water species suggests that this stage is somewhat more temperate than the upper cold-water stage. A distinct tendency toward warm water is represented in samples 48–51 in which *Globigerina pachyderma* shows a decrease in frequency and in which three warm-water species show more occurrences and higher frequencies than in the zone above. The samples below sample 51 indicate continued cool to cold water, and this fauna continues to the bottom of the core.

SIZE DISTRIBUTION

The size group means represent that point at which 50 per cent of the specimens in a species belong to a larger size group and 50 per cent belong to a smaller size group. A discussion of the apparent trends of mean sizes for a few of the most indicative species is here related to the water-temperature interpretations.

Globigerina pachyderma is a cold-water species which occurs throughout most of the samples of the cores 7-41 and 9-41 but with varying frequency. The size means in these two cores show opposite trends. In core 7-41 *G. pachyderma* generally appears to remain below size mean 1.5 in warm stages and varies from 1.5 to 3.0 in cold stages. In core 9-41 it remains mostly above 1.5 in the warm-water stages and below 1.5 in the cold-water stages. This suggests that a change in size occurs in *G. pachyderma* at the same time as this species changes in frequency, but the direction of change is inconsistent and cannot be explained at present.

Globigerina bulloides indicates the same change as the above species; it generally changes from below 1.5 in the warm-water stages to above 1.5 in the cold-water stages of core 7-41 and above 1.5 in the warm-water stages to below 1.5 in the cold-water stages in core 9-41. This indicates that a change in mean size accompanies a change in frequency, but no absolute correlation with the temperature is possible.

Globorotalia menardii, a very warm-water type, shows marked decrease in size mean as its frequency drops when approaching a cold-water stage, especially in core 9-41. *G. menardii* increases in size as the water becomes warmer.

Generally, the warm-water species appear to change their mean sizes in response to a change in water temperature.

DISCUSSION

GENERAL STATEMENT

Interpretation of the Foraminifera in submarine cores is mainly a problem in ecology. Most of the species and over 90 per cent of the specimens in these samples are pelagic, and these Foraminifera are presumed to inhabit the upper layers of oceanic water. Pelagic species do not necessarily float awash but live somewhere above the bottom. They live mainly in the top 100 meters according to data collected in the South Atlantic by Schott (1935). Only living species collected from plankton tows can be considered definitely pelagic in habitat; a list of known pelagic Foraminifera is given by Cushman (1940).

Although it usually is assumed that the pelagic assemblage in bottom sediments indicates conditions in the upper layers of water, this is not necessarily true. Phleger (1945) collected larger populations of living pelagic Foraminifera at 800 to 1000 meters than at 100 meters at two localities in the western North Atlantic, but these data need further verification. (*See* Phleger, 1942, p. 1094–96.)

INTERPRETATION OF CORE FAUNAS

Temperature changes.—Four water-temperature stages are suggested by the faunas in the cores. (*See* Figure 3.) From top to bottom of the cores they are as follows: (1) the present warm-temperature water stage with a warm maximum in core 9-41 a short distance below its top; (2) a cold-water stage; (3) a warm-temperate water stage; (4) a cold-water stage extending to the bottom with a possible cool-temperate water indicated just above the bottom of the cores.

Cushman and Henbest (1940, Figs. 11–21) found two or more Arctic or sub-Arctic faunas, separated by warm-water faunas, below the tops of the cores taken from the North Atlantic at North Latitude 36° to 49.5°. Phleger (1939, Figs. 2–4; 1942, Pl. 3) indicates at least one cold-water fauna beneath the modern fauna, represented by changes in the pelagic and benthonic assemblages, in cores from the continental slope of the western North Atlantic. The two warm-water and the two cold-water stages described in cores 7-41 and 9-41 appear to be comparable to the upper stages identified in these other North Atlantic cores.

The upper warm-water fauna appears to have a maximum development below the top in core 9-41. Deevey (1939, Table 1) has found evidence, in pollen analysis of Connecticut lake sediments, of a postglacial optimum about midway between the last deglaciation and the conditions now obtaining in the region. Deevey correlates this optimum with evidence collected by Auer in Eastern Canada, McCulloch in New York, Sears in Ohio, and Voss in Wisconsin. Phleger (1939, p. 1416) has found a post-Wisconsin foraminiferal fauna indicating warmer surface-water conditions than now obtained. He correlated this with the postglacial optimum suggested by the pollen-analysis studies. Possibly the upper "warmer-than-present" assemblage in core 9-41 is an oceanic evidence of the postglacial optimum recognized on the nearby land.

Ray (1940, p. 1912–13) has identified five Wisconsin substages in the southern Rocky Mountains, each separated by a warmer interim. Substages of the Wisconsin have been identified in northern Europe which may be correlatives of the Rocky Mountain stages (Ray, 1940, p. 1914). It is suggested that the warm- and cold-water faunas identified in Atlantic cores by Cushman and Henbest (1940) and Phleger (1939; 1942) and faunas apparent in the present cores may be correlated with the subdivisions of Wisconsin time rather than with other major glacial stages of the Pleistocene.

Climatic changes would be reflected in the temperature of adjacent oceanic water, and in the western part of the North Atlantic changes in the course of the Gulf Stream probably would be associated with climatic changes.

These cores were obtained from an area near the edge of the Gulf stream, which

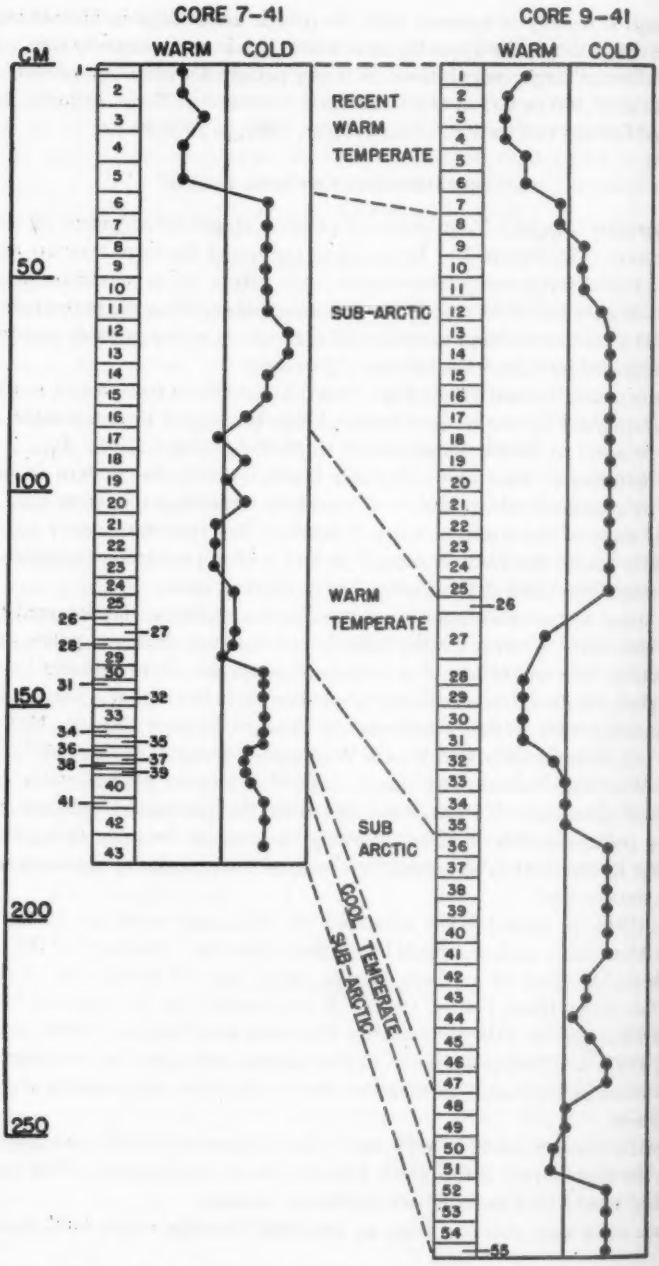


FIGURE 3.—*Approximate relative water temperatures indicated by the foraminiferal faunas in the cores*

suggests that minor changes in water temperature, indicated by faunal variations, may be due to shift in the position of Gulf Stream water masses not necessarily associated with prolonged climatic changes. Small faunal variations might be due to the movements of counter currents and eddies into areas of lower or higher water temperature. According to Iselin (1936) the northeasterly portion of the Gulf Stream, the North Atlantic Current, contains many such counter currents, eddies, and bodies of dead water whose temperatures differ from that of the main current. From this approximate area, Cushman (1920–1931) records occasional occurrence of species foreign to the apparently normal fauna.

Cushman and Henbest (1940, p. 47) suggest rafting of specimens by seaweed and ice into areas foreign to their normal environment. These methods account for unusual occurrences of a few specimens, but they are not the only possible explanations for samples which are radically different from those above or below them, at least not in the area covered by these cores under the present ecologic conditions. Comparatively sudden shift of a mass of warm water into an area previously foreign to it would cause a deposition of pelagic species characteristic of the water. It might also upset the ecology of the entire water column. If the temperature-range tolerance of some species is as limited as records of distribution suggest, then the sediments deposited in such an area would contain: (1) an abundance of the fauna living in the area immediately before the change occurred; (2) abundance of species living in the warm mass of water which moved into the area. The result may then be the deposition of a sample resembling a transitional fauna. If considerable cooling of the entire water mass eventually occurs, causing high mortality, the number of specimens deposited during such a short stage would represent a shorter period of time than the same number of specimens accumulated under stable conditions.

SIZE TRENDS

Pelagic species.—The results of the study of size trends are not conclusive and raise more problems than they solve. There appears to be some indirect relationship between the size mean of some species and water temperature. A change in mean size often occurs coincident with the faunal changes presumed to be due to temperature changes. Thickness of test has not been studied in detail, although warm-water samples appear to have thicker tests than those in cold-water samples.

Changes in mean size within the cores may be either abrupt or distributed through a transitional layer. The same species have not changed in relation to water temperature in the same manner in all cases in these cores, and this makes interpretation difficult. Some species do not enter a fauna with a large mean size but attain a mean of 1.5 or larger size group only after having become firmly established as an addition to the fauna. This appears to accompany a reduction in mean size of one or more other species. The appearance of a species not previously present in a locality may cause withdrawal or decrease in frequency of occurrence of certain other species. Thus no sample was found to contain an equally high frequency of both *Globigerina bulloides* and *G. inflata*, and the mean size of the one in greater abundance in a sample is usually larger than the size mean of the other. In general, the mean size of a species appears to be greatest when the frequency of occurrence of the species

is high and the water temperature (ecologic conditions) apparently has attained an optimum for the species. A smaller mean size is common for species of low frequency of occurrence.

A summary of possible causes of size limitation might be: (1) water temperature; (2) genetic constitution; (3) size averages determined by casualties of juvenile forms caused by some ecologic factors such as temperature or change in food supply. Mechanical sorting of the sizes comparable to the sorting of sediments by currents also is a possibility.

Benthonic species.—The benthonic group is masked by the quantity of pelagic specimens in these cores. (*See* Cushman and Henbest, 1940, p. 48, for a similar condition in other cores.) The number of benthonic specimens in the present samples is insufficient for any relationships between size and known factors of distribution to be of any value. The benthonic forms in this area generally tend to have larger mean sizes than the pelagic forms. *Uvigerina peregrina* is an outstanding example of large size, while *Elphidium incertum*, particularly in core 9-41, is generally quite small.

FUTURE WORK

Study of these two cores has demonstrated the usefulness of the continuous method of sampling for Foraminifera since minor variations in ecologic conditions are more readily indicated than in widely spaced samples. Additional cores should be obtained and studied by the continuous sample method on a quantitative basis to obtain an accurate picture of vertical faunal variations and their implications. The study of sizes is so suggestive that it should be explored further. The present paper indicates only one method of investigation.

More adequate information on the ecology of Foraminifera is absolutely essential. Quantitative collection of living pelagic Foraminifera from various water depths and various environments will supply data on relationships to temperature and to the remainder of the plankton. These collections should be seasonal. Experimental work on life cycles and on temperature relationships should be an aid in these problems but will be difficult of execution.

CONCLUSIONS

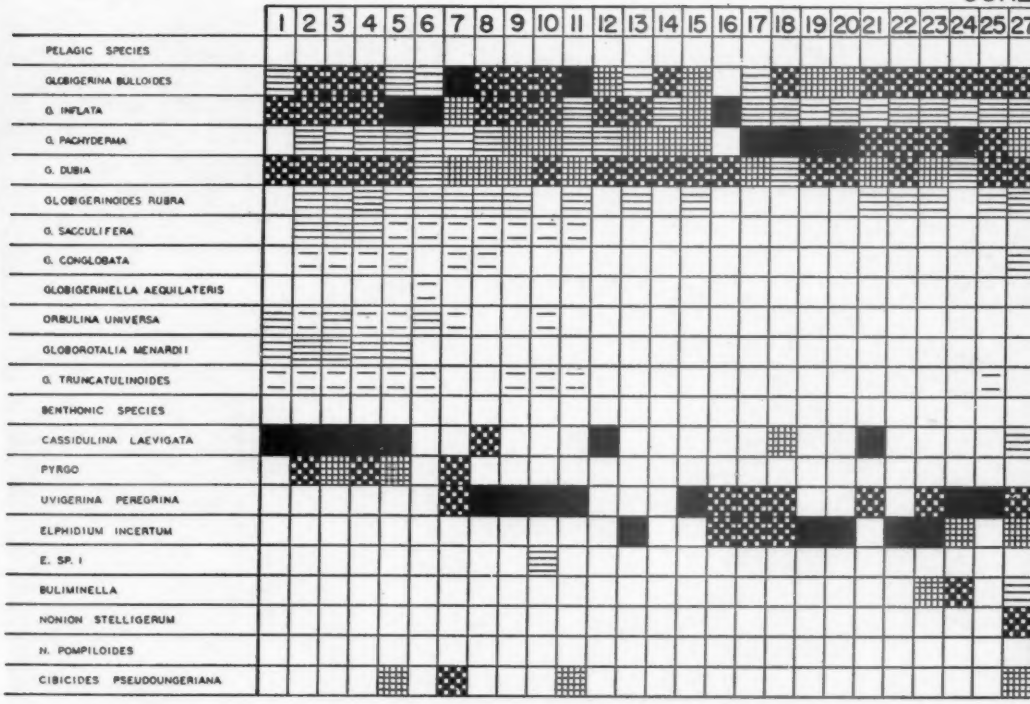
(1) Two cores from the basin of the North Atlantic contain two sub-Arctic faunas separated by a warm-temperature fauna. The sub-Arctic faunas are interpreted as representing the two latest stages of the Wisconsin.

(2) A post-Wisconsin fauna in core 9-41 indicating warmer surface waters than obtain at present apparently is correlated with the postglacial "optimum."

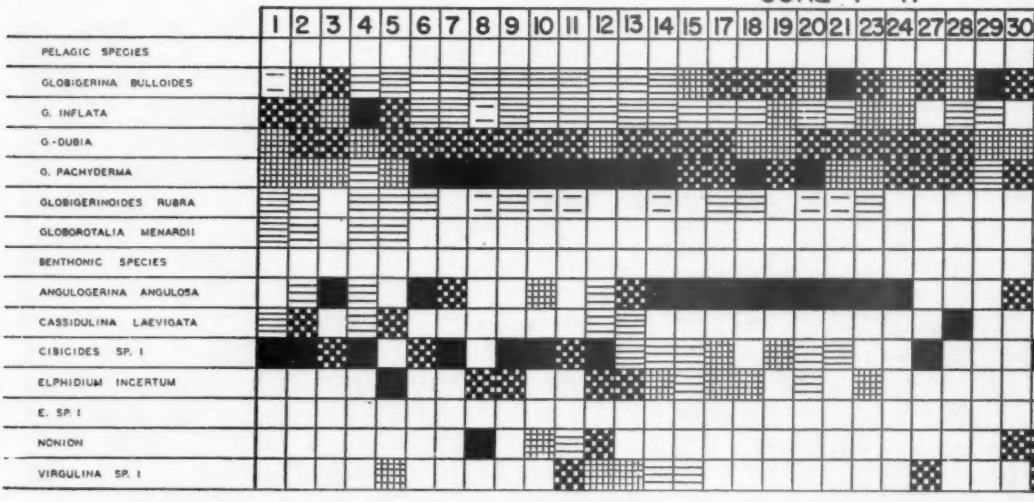
(3) Continuous sampling of the cores has revealed minor faunal variations which may be due to intermixing of water masses of different temperatures.

(4) Studies of size groups suggest a possible relationship between mean size and water-temperature conditions in some species.

CORE

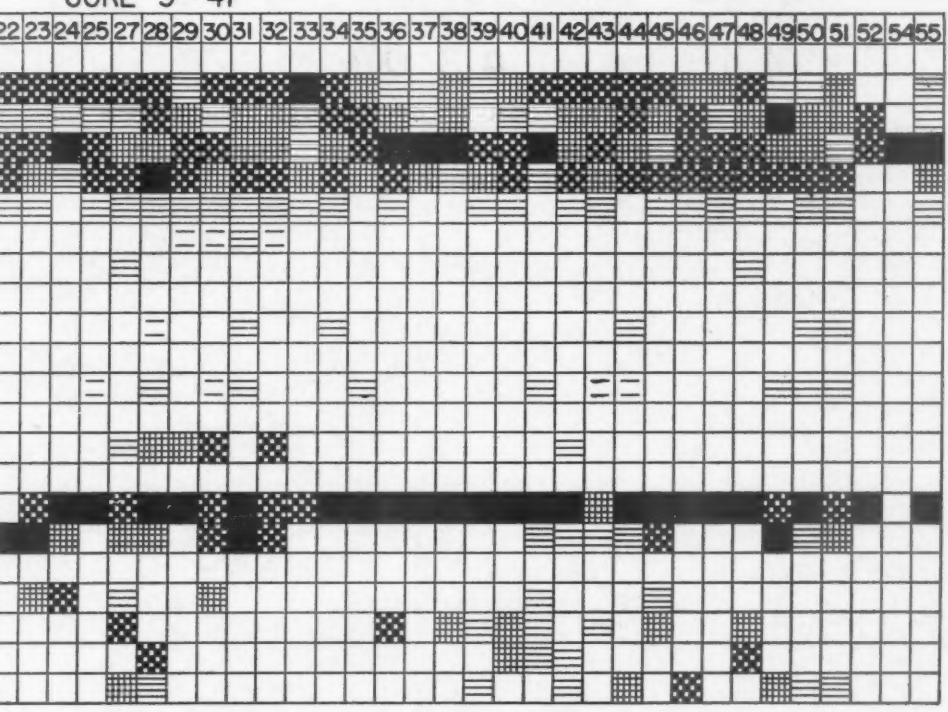


CORE 7-41



PERCENTAGE FREQUENCY GROUPS OF SPECIES OF FOR

CORE 9–41



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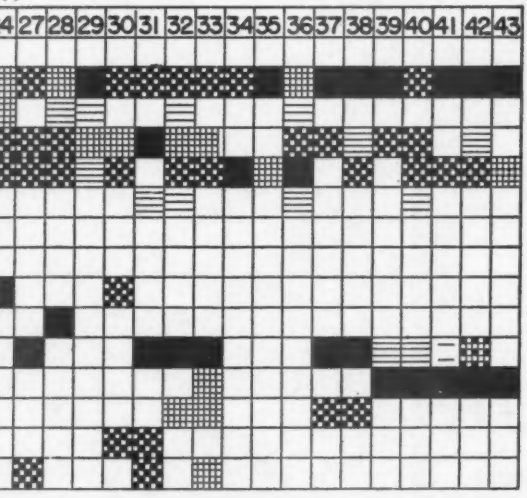

LESS THAN 1%

1–5%

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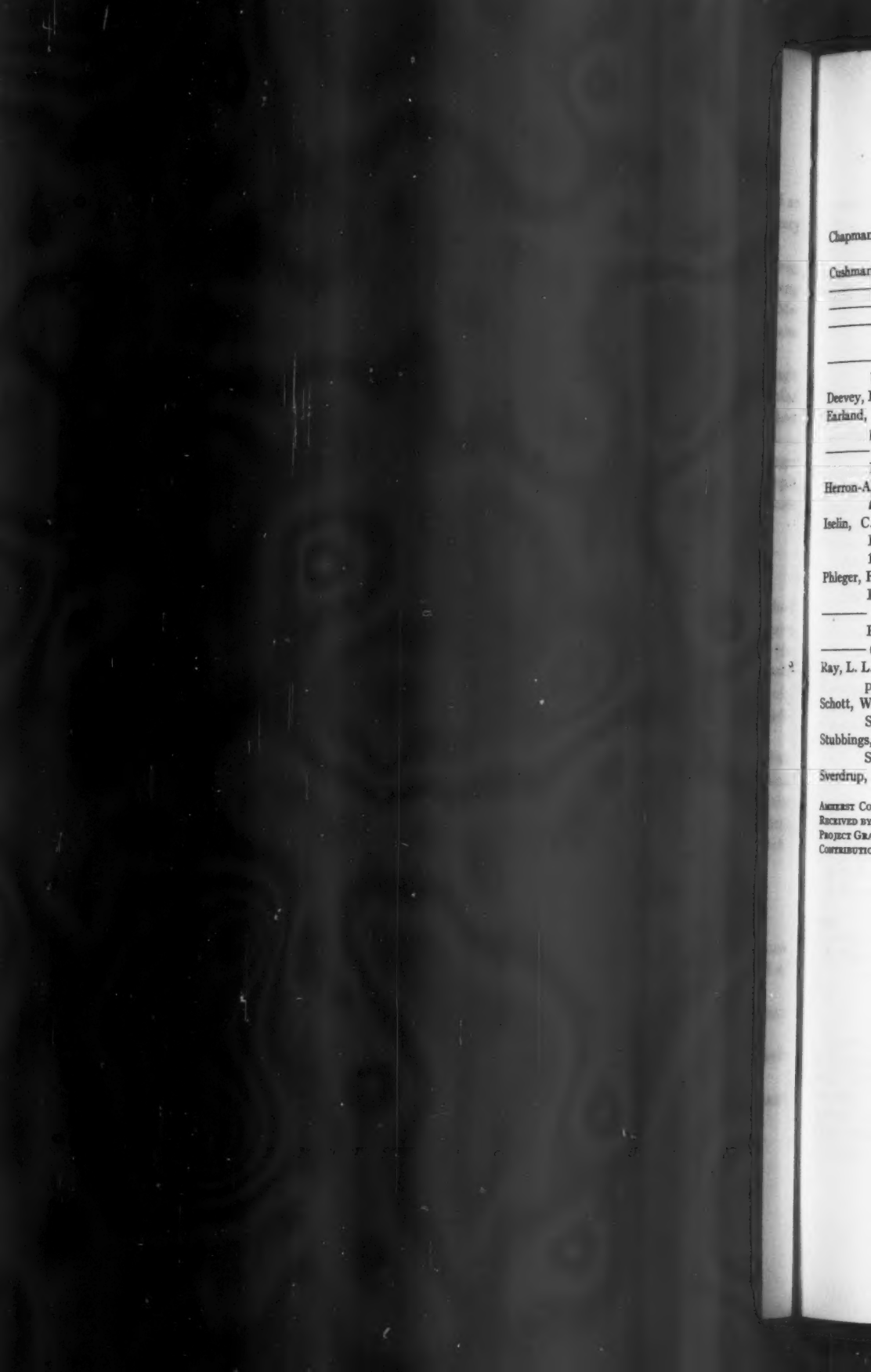
MORE THAN 50%

IES OF FORAMINIFERA IN THE CORE SAMPLES



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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 967-984, 2 PLS., 3 FIGS. OCTOBER 1946

BRUCITE DEPOSITS IN THE RUTHERGLEN DISTRICT, ONTARIO

BY M. L. KEITH

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ABSTRACT

Some deposits of brucitic limestone with a ratio of MgO:CaO higher than that of dolomite are described. Evidence is given to show that the excess magnesia derived from dissociation of dolomite by the heat of the adjacent granite. Selective transfer of the products of dissociation into the carbonate rocks is attributed to igneous emanations. The bulk of the brucite is believed to have been deposited by direct replacement of carbonates, rather than by hydration of previously formed periclase, as has been suggested for similar occurrences elsewhere.

INTRODUCTION

The Rutherglen District takes its name from the village of Rutherglen, on the Canadian Pacific Railway between Mattawa and North Bay, about 180 miles due north of Toronto (Fig. 1).

North of Rutherglen, within an area of about 5 square miles, much of the crystalline limestone[1] exposed contains disseminated brucite ($Mg(OH)_2$). Most of the known deposits are in Olrig Township on the north side of the Mattawa River. Somewhat similar deposits of brucitic limestone are found at Bryson in the Ottawa valley, at Wakefield along the Gatineau River north of Ottawa, and near Wilkinson in southeastern Ontario. The writer describes the main features of the Rutherglen deposits, compares them briefly with the deposits at Wakefield and Bryson, and makes some deductions regarding the genesis of brucitic limestone.

FIGURE 1.—*Index map showing location of Rutherglen district and other districts where brucitic limestone occurs in Ontario and Quebec*

The occurrence of crystalline limestone along the Mattawa River was known as early as 1820 (Bigsby, 1850 and Barlow, 1899). Sir William Logan (1847) and others examined outcrops of crystalline limestone at Talon Chute, which is on a well-travelled canoe route of the early days, but the brucite content of the rocks was not recognized until the investigation of Goudge in 1937 (Goudge, 1939). The pioneer work on commercial development of brucitic limestone in Canada was done by

[1] For the sake of simplicity the term "limestone," except where qualified in the text, is used in a broad sense, including calcium limestone and dolomitic limestone.

Goudge. Other descriptions of Canadian occurrences of brucitic limestone are those of Osborne (1939), Brown (1943), and Ambrose (1943). The writer's investigation was undertaken for the Aluminum Company of Canada Ltd., and Aluminium Laboratories Limited in the summers of 1942 and 1943.

TOPOGRAPHY

Topography of the district is partially controlled by the strike of the rock formations. Main granite ridges trend east to southeast and rise 100 to 150 feet above the Mattawa and its tributaries. Topographic expression of the limestone areas is not pronounced, although brucitic bands in the limestone in some cases form low ridges. Some minor ridges have a northeasterly trend, parallel to the direction of glaciation. Heavy glacial drift covers part of southern Olrig Township, but almost half the area shows rock formations either outcropping or covered by only a thin mantle of soil.

TABLE OF GEOLOGICAL FORMATIONS

Following is a geological table for the Rutherglen District:

Recent and Tertiary		boulder till sand clay
Pre-Cambrian Post Grenville	Intrusives	granite pegmatite, pegmatitic quartz garnetiferous granite gneiss and syenite gneiss (type 1) fine-grained mica granite with inclusions of highly granitized quartzite and siliceous gneiss (type 2)
Pre-Cambrian Grenville	Contact Rocks	contact silicate rocks—principally diopside, phlogopite massive serpentine and mottled serpentine-carbonate mixtures
	Metamorphosed Sedimentary Rocks	brucite-bearing crystalline limestone and dolomite nonbrucitic crystalline limestone and dolomite (mostly highly serpentinized) dark paragneiss, amphibolite, metamorphic schists

STRUCTURE

Crystalline limestone and dolomite of the Grenville series occur as shallow, lenticular roof pendants within a large granite batholith whose limits are outside of the area investigated. Distribution of the limestone remnants is shown on a general map of the region (Fig. 2). The crystalline limestone is closely folded and in places has undergone extreme plastic deformation. High-calcium limestone exhibits high mobility under load and in places invades and disrupts bands of apparently less mobile dolomitic limestone.

Major fold axes strike N. 50°–60°W., parallel to the general direction of elongation of the limestone roof pendants and the regional strike of gneissic structure in the

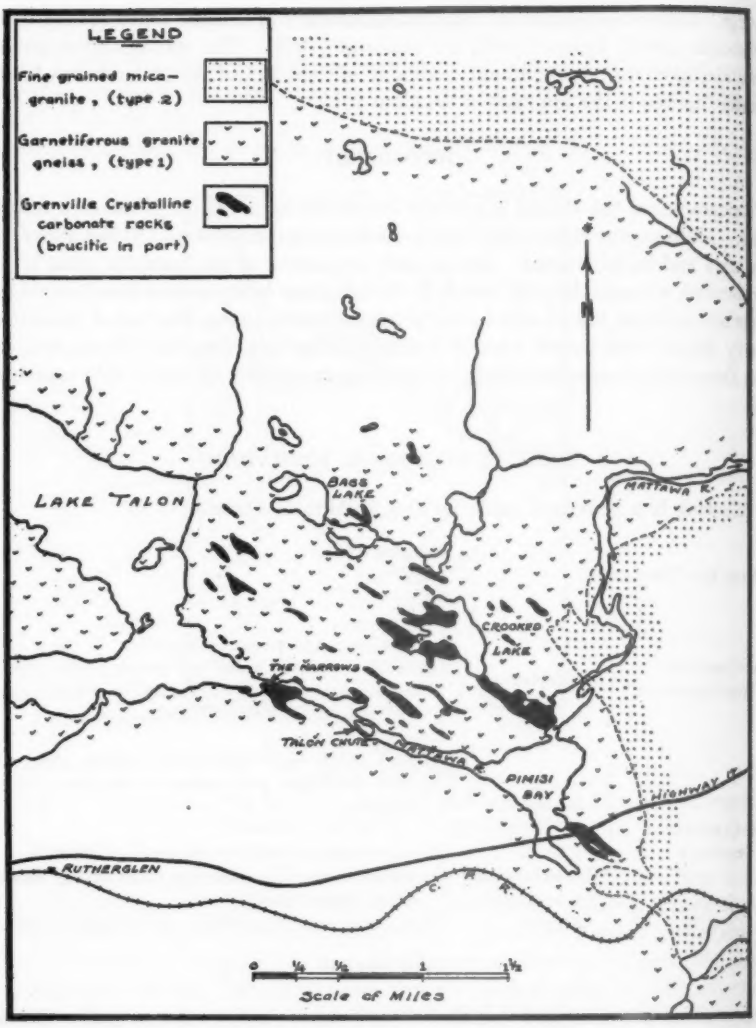

FIGURE 2.—*Generalized geologic map of Rutherglen district*

enclosing granite. In most cases close folds of the sedimentary rocks are overturned to the north so that dips are vertical or steep to the southwest. Structures could not be worked out in detail because of the difficulty of distinguishing between primary and metamorphic banding in the carbonate rocks. The general shape and character of the limestone remnants are illustrated by a block diagram of one of the brucitic limestone deposits as outlined by drilling (Fig. 3).

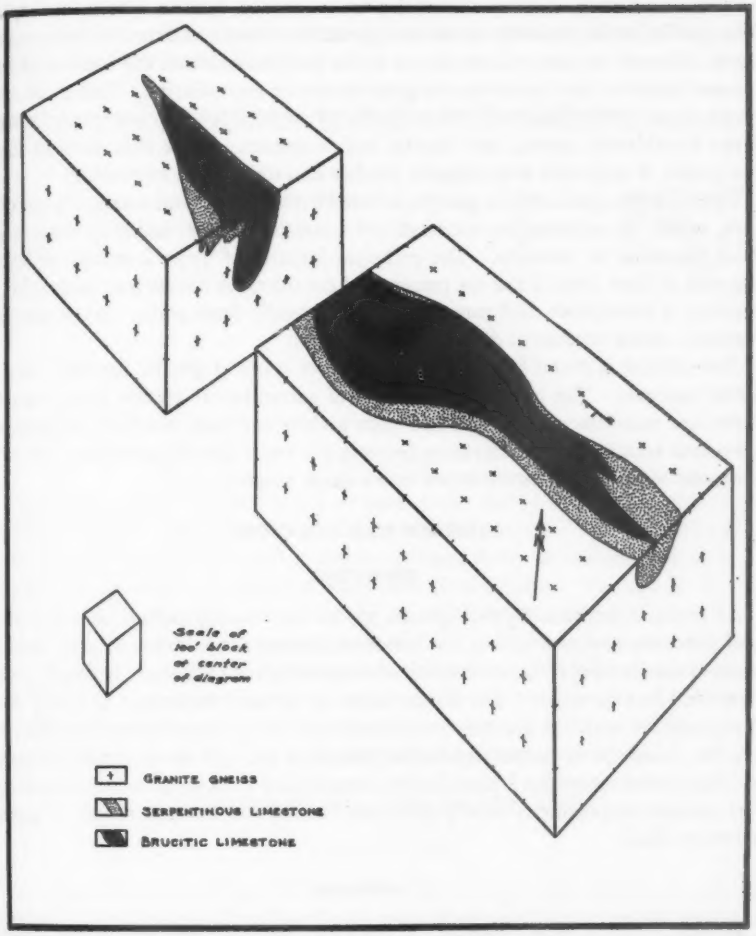

FIGURE 3.—*Block diagram showing the shape and character of one of the roof pendants of brucitic limestone*

INTRUSIVE ROCKS

There are two main types of granite in the region. Nowhere in the area is one granite found to cut the other. Type 1, the rock which encloses the limestone remnants, is a medium-grained pink granite gneiss, of uniform texture and color over wide areas and containing 1–5 per cent of small red garnets. Thin sections of typical specimens show predominant orthoclase, some microcline and replacement microperthite, plus, in decreasing order of abundance, plagioclase feldspar (Ab_{86}–Ab_{91}), quartz, hornblende, garnet, and biotite. Some specimens show coronas of garnet

around hornblende. Minor accessories are magnetite, apatite, zircon, and sphene. The granite gneiss generally shows no appreciable change adjacent to limestone contacts, although in some places narrow dykes in limestone and the borders of larger masses intrusive into limestone are gray syenite or syenodiorite. Under the microscope, these border phases are seen to consist of perthitic feldspar intergrowths, strong green hornblende, garnet, and biotite, but no quartz. Some thin sections show a few grains of carbonate and irregular patches and stringers of serpentine.

Type 2, a fine-grained mica granite, is found in the eastern and northern parts of the area, where the sedimentary remnants are quartzite, arkose, and mica schist rather than limestone or dolomite. The principal features of Type 2 granite which distinguish it from Type 1 are the presence of considerable biotite and muscovite, the absence of hornblende and garnet, and the generally finer grain. Some specimens contain a minor amount of disseminated graphite.

No evidence is found to suggest that the two types of granite represent two different magmas. The common occurrence of garnetiferous granite gneiss enclosing carbonate xenoliths and fine-grained mica granite enclosing siliceous xenoliths suggests that compositional differences between the two types of granite are due to the character of wall rocks incorporated into a single magma.

CONTACT SILICATE ROCKS

SERPENTINE

At contacts between Type 1 granite gneiss and the crystalline limestone of the roof pendants and also within the limestone masses away from contacts, there are zones of massive serpentine or intermixed serpentine and carbonate, from a few inches to several feet in width. The border zones of massive serpentine generally are in sharp contact with the granite; away from the contact they commonly grade into brucitic limestone or barren crystalline limestone through an intermediate zone in which granular serpentine is abundantly disseminated throughout a carbonate matrix. The massive serpentine is mostly yellowish brown, and through shades of greenish brown to black.

DIOPSIDE

Bodies of almost pure diopside are common, although less widespread than the massive serpentine. Diopside occurs in beds and lenses which appear to parallel the bedding of the crystalline limestone. The smaller island in the southwest arm of Crooked Lake consists entirely of a pale greenish-white diopside rock with a fine-grained sugary texture. Diopside makes up over 95 per cent of the rock. Other constituents are carbonate and a few disseminated grains of galena, pyrite, and sphalerite. Somewhat similar diopside rocks are found in the western part of the map area, near Lake Talon. These differ from the Crooked Lake outcrop in that they are faintly banded, finer-grained, and contain 5 to 10 per cent of bronze-colored phlogopite in fine disseminated flakes. The largest known body of diopside in the district is a lens 700 feet long and 100 feet in maximum width, along the north contact of a dolomitic limestone band about quarter of a mile northeast of Talon Chute.

The exposures are white to greenish white and show a distinct foliation parallel to the granite contact. Thin sections of typical specimens consist of diopside, 90 per cent, microcline and cordierite, 10 per cent.

TABLE 1.—*Chemical analysis and optical data of phlogopite*

SiO_2	41.58	
Al_2O_3	8.81	
Fe_2O_3	1.16	biaxial negative
CaO	.84	2V small
MgO	31.40	N_m 1.572 ± .004
Na_2O	.32	$N_p < 1.539$
K_2O	6.14	birefr. .035 approx.
H_2O	8.40	
TiO_2	.12	
F_2	.93	
	99.70	

PHLOGOPITE

Phlogopite, which is found in the diopside zones and in association with massive serpentine, shows some variations in color and composition. One exploration drill hole cut a contact zone consisting entirely of small flakes of pale-greenish mica very loosely held together. Some of the flakes have silvery luster. Through the kindness of Mr. M. F. Goudge, an aggregate of the green flakes was analyzed by Mr. R. J. C. Fabry of the Geological Survey of Canada. The analysis, and the writer's optical data, are given in Table 1. Aluminum Company of Canada laboratories at Arvida and Wakefield made partial analyses on material from the same zone, and the results show higher alumina and lower magnesia than indicated in Fabry's analysis. The analyzed material probably is phlogopite partially altered to chlorite.

METAMORPHOSED SEDIMENTARY ROCKS

GNEISSIC ROCKS

The Grenville series in the Rutherglen District is composed mainly of crystalline limestone with some narrow bands of metamorphosed clastic rocks, principally hornblende paragneiss. The gneissic rocks are generally dark, small red anhedral garnets are common, potassium feldspar generally is predominant over plagioclase, and hornblende is more abundant than biotite. Quartz content varies from 5 to about 90 per cent but is less than 20 per cent in most specimens. Minor constituents are muscovite, diopside, serpentine, magnetite, limonite, chlorite, apatite, graphite, pyrite, carbonates, and titanite.

CRYSTALLINE CARBONATE ROCKS

The crystalline carbonate rocks are predominantly magnesian, although all variations through dolomitic limestone to pure calcium limestone can be found.

There is also a wide variation in grain size, from a minimum of less than 0.5 millimeter to a maximum of over a centimeter. Most of the very coarse-grained rocks are nearly pure dolomite, although a few occurrences of coarse calcium limestone can be seen along the Mattawa River at the Narrows.

In addition to dolomite and calcite, the other common minerals in the limestone are brucite and serpentine, including serpophite, an amorphous mineraloid of serpentine composition (Rogers and Kerr, 1942, p. 362).

There are bands of diopside in places, but disseminated grains are rare. Very sparsely distributed are small grains of magnesia spinel and forsterite, which show all stages of alteration to serpentine. Alteration of forsterite produces serpentine granules with a reticulated structure, and composed partly of serpophite. Alteration of spinel produces radiated serpentine (Pl. 2, figs. 2-4).

Magnetite is abundant in parts of some occurrences, practically absent in others. The following minor constituents have been identified in the limestone: hematite, pyrite, pyrrhotite, limonite, phlogopite, graphite, quartz, rutile, scapolite, and the rare mineral pyroaurite (Goudge, 1939, p. 13; Ellsworth, 1939).

METHODS OF DISTINGUISHING MINERAL CONSTITUENTS

The amount of granular brucite in a specimen can be estimated roughly from examination of a naturally etched weathered surface. Generally, brucite is more soluble than carbonates in surface waters, and its removal leaves a characteristic pitted surface. A chalky-white or buff alteration product, probably hydromagnesite (Goudge, 1939, p. 4), lines the cavities from which brucite has been removed. Normally, the pitting does not extend more than a quarter of an inch below the surface.

On some outcrops serpentine exhibits superior resistance to erosion and forms nodules which protrude above the level of the carbonates. In other occurrences serpentine shows lower resistance and is partially pitted at the surface. As a rule pits or honeycomb structures from which serpentine has been removed contain a skeleton residuum of rusty siliceous material. The observed variation in weathering of serpentine may be due to compositional differences in the serpentine itself or to different conditions of weathering. Serpentine generally protrudes on a bare rock surface but weathers more rapidly where outcrops have a thin mantle of soil and moss.

In fresh unweathered specimens, some care is required in distinguishing serpentine from brucite and calcite from dolomite. The higher birefringence of brucite distinguishes it from serpentine in thin section, but in hand specimens it is necessary to use chemical stains to assist estimation of mineral proportions and study of textures. The following staining methods are found most useful:

(1) The specimen is immersed in dilute hydrochloric acid in which a few crystals of potassium ferrocyanide have been dissolved (some specimens react more quickly with potassium ferricyanide). Immersion time varies and can be judged by examining the progress of the staining reaction. Brucite is stained blue, and serpentine is stained pale green. Calcite and dolomite are unaffected unless the immersion time is greatly prolonged.

In the next step, the specimen is washed gently and immersed in Lemberg solution[2] for about 1 minute. This procedure stains calcite a strong violet, leaves dolomite white, and has very little effect on the stained brucite (Pl. 1, fig. 1).

(2) A 2½ per cent aqueous solution of ferric chloride may be used instead of Lemberg solution (immersion time 10 to 30 secs.). Ferric chloride produces an orange-

TABLE 2.—*Chemical analyses of brucitic limestone and recasts to mineral proportions*

	Chemical Analyses				Mineral Proportions		
DEPOSIT	A	B	C		A	B	C
SiO_2	0.90%	1.48	0.61	Serpentine	2.0	3.4	1.4
R_2O_3	0.47	0.47	0.28	Brucite	22.5	12.8	20.2
CaO	26.9	27.5	23.6	Dolomite	60.1	75.6	75.3
MgO	29.5	27.0	31.6	Calcite	15.4	8.2	1.5
CO_2	35.4	39.5	37.0	Hydromagnesite	—	—	1.6
H_2O	7.2	4.4	6.7				
Total	100.4	100.4	99.8		100.0	100.0	100.0

yellow stain on calcite, leaves dolomite white, and does not destory the brucite stain. The stain produced by ferrric chloride is easily rubbed off. The principal advantage of this method is that the ferric chloride solution is easier to prepare than Lemberg solution. For thin sections, the ferric-chloride treatment may be used alone without preceding treatment to stain brucite.

When additional contrast is desired, following immersion in ferric-chloride solution, a specimen may be washed and, while still wet, immersed, in a solution of ammonium sulphide saturated with hydrogen sulphide. Calcite is stained jet black almost immediately. The stain turns brown on exposure and is easily smudged.

(3) For crystalline carbonate rocks the blue calcite stain produced by immersion in copper nitrate solution (John Rogers, 1940) gives less uniform results than either Lemberg solution or ferric chloride.

PETROGRAPHY OF THE BRUCITE DEPOSITS

In the Rutherglen area, brucite ($Mg(OH)_2$) is found disseminated in medium-grained magnesian limestone of the Grenville series in amounts varying from 12 per cent to 24 per cent (averages for different deposits). Individual specimens contain up to 34 per cent brucite. Associated minerals in the brucitic limestone are principally serpentine, magnetite and hematite (in sections of some deposits), and very minor amounts of spinel and forsterite in minute grains. Although massive diopside occurs in places adjacent to brucitic limestone, no disseminated diopside is found in the brucitic zones of the limestone.

The composition of some typical deposits in the Rutherglen District is shown in Table 2.

[2] To prepare Lemberg solution boil for 20 minutes a mixture of 6 gms. logwood extract, 4 gms. $AlCl_3$ and 60 cc. of water, adding water to replace that lost by evaporation. Cool and filter for use.

In individual samples of brucitic limestone, the ratio of calcite to dolomite is widely variable, but the calculated average ratios for deposits fall within a narrower range, from 37:63 to 0:100. Average ratio of calcite to dolomite for all deposits is 15:85. This is significantly different from the proprotions in the Wakefield deposits, in which calcite is predominant. In the Rutherglen brucitic limestones the molecular ratio MgO/CaO is considerably higher than that of pure dolomite. In contrast, the same ratio for Wakefield and Bryson brucitic limestones is slightly lower than that of dolomite.

In most of the deposits brucite is distributed in distinct layers in the limestone. Adjacent layers commonly contain granular serpentine instead of brucite. This layered distribution is by no means completely selective. There is almost always some serpentine in brucitic bands and a minor amount of brucite in serpentine-rich bands. Bands are spaced at intervals of from a few inches to tens of feet. In places there are wide bands of limestone or dolomite with neither brucite nor ser-serpentine in appreciable amount. Field observations suggest that the banding generally coincides with original bedding planes of the limestone.

Brucite exhibits three forms: It occurs as granules of two types, as thin micaceous plates, and as narrow veinlets. Most of the brucite is in irregular and rounded grains ranging from less than 0.5 mm. to about 3 mm. The granules are milky white to buff in hand specimen, rarely gray or black; they are colorless or faintly brownish under the microscope. Within one layer of the limestone, granule size and color are fairly constant, but in many cases adjacent layers show wide differences. In two thin sections small rounded masses of serpentine occur within granular brucite, but otherwise there are no inclusions in brucite granules. The brucite granules occur in both dolomite and calcite. Figure 1 of Plate 1 illustrates the texture of a typical specimen.

The shape of brucite granules shows some differences depending upon whether the matrix is calcite or dolomite. Brucite grains within calcite generally are rounded, whereas brucite grains within dolomite exhibit angular outlines which conform to the carbonate cleavages (Pl. 1, fig. 2). The dolomite immediately surrounding a brucite granule is commonly clouded with minute inclusions of an unidentified opaque mineral (Pl. 1, fig. 3). No such halo is seen where the matrix is calcite. Projecting tongues or veinlets of brucite in some cases extend from both angular and rounded brucite granules into the surrounding carbonate, along cleavages or grain boundaries.

Granular brucite commonly has a flaky internal texture, and the fine flakes form intricate patterns visible under the microscope with crossed nicols. Some grains, particularly those within calcite, have a concentric "onion-skin" texture with flakes or fibers differently oriented in each succeeding layer, but these are less common than in specimens from Wakefield.

The foliated or micaceous form of brucite is not easily seen in hand specimens of the crystalline limestone. The folia are small and white to pale greenish white. In thin section they appear as colorless, low-relief crystals commonly shaped like a double-pointed wedge. This form of brucite is restricted to calcite, and the folia are abruptly terminated where they come up against dolomite (Pl. 2, fig. 1). Many of the observed textures strongly suggest the breakdown of dolomite to an intergrowth

of calcite and brucite. Where granular brucite comes in contact with the foliated form, the wedge-shaped folia generally project a short distance into the granule, and in some cases the projecting ends seem to be shredded and partially replaced or deformed.

Vein brucite is rare; it is encountered occasionally in drill core, and veinlets up to half an inch in width occur at a quarry in the western part of the area, where the veinlets cut across the banded structure of the limestone. They are composed of pale-green translucent brucite with a pearly luster and show one good cleavage oriented nearly at right angles to the vein walls and extending continuously from wall to wall.

There is some serpentine in all the brucite deposits. Reference has been made to the bodies of massive serpentine which occur at granite-limestone contacts as well as within the limestone roof pendants. The distribution and general appearance of granular serpentine are similar in many respects to those of granular brucite. Serpentine granules commonly are white or pale yellowish white, less commonly green to brown. The grains generally are rounded rather than angular irrespective of whether they occur in calcite or dolomite. As a rule they are smaller than brucite granules in the same specimen.

Serpentine granules exhibit two types of internal texture under the microscope. Most of them show a network pattern and are composed of antigorite and serpophite; others are radiated and composed of antigorite only. In a few cases small remnant cores of forsterite are found within granules of the network type, and probably much of this type of serpentine is derived from forsterite or in part from diopside. The radiated type of granular serpentine seems to be secondary after magnesia spinel; remnants of spinel observed in thin sections from several Rutherglen deposits show all stages of progressive alteration to radiated serpentine (Pl. 2, figs. 2-4).

A careful search in a large number of representative specimens and thin sections shows no periclase cores similar to those described in brucitic limestone from Riverside, California (A. F. Rogers, 1918, p. 581; 1929, p. 462), from the Organ Mountains, New Mexico (Dunham, 1936, p. 315; Hunt and Faust, 1937, p. 1154), and from Wakefield, Quebec (Ambrose, 1943, p. 18).

Magnesia spinel may easily be confused with periclase. Therefore, in view of the above reported occurrences of periclase in brucite, the identity of all separated isotropic grains was carefully checked, both by optical methods and by X-ray powder photographs[3]. Included in the study were isotropic grains from a group of Rutherglen specimens, from one Wakefield specimen kindly supplied by Doctor Ambrose, and from a specimen of brucitic limestone from Riverside, California, supplied by Prof. A. F. Rogers. The Rutherglen and Wakefield samples and the bulk of the Riverside sample proved to be magnesia spinel. Two small grains in the concentrate from the Riverside specimen probably are periclase (N above 1.716).

The spinel grains are less than 0.5 mm. in diameter, isotropic, colorless in thin section, and with an index of refraction of $1.716 \pm .003$. They are practically insoluble in hot hydrochloric acid. The grains generally contain regularly oriented inclusions

[3] X-ray photographs by M. J. Buerger of Mass. Inst. Technology and L. G. Berry of Queen's University.

of some platy birefringent mineral, too small to be identified. In some specimens the spinel grains are visible with a hand lens; they are pale pink or violet and may easily be mistaken for garnet.

In parts of some deposits, notably those near Bass Lake and Otter Lake, magnetite is found disseminated to an amount as much as 20 per cent, in small replacement

TABLE 3.—*Chemical analyses and recasts of cellular limestone (P) and cellular limestone impregnated with magnetite (M)*

Chemical Analyses			Mineral Proportions		
	P	M		P	M
SiO_2	0.73	0.81	Magnetite	0.9	20.3
$FeO + R_2O_3$	0.96	20.49	Serpentine	1.8	1.8
CaO	27.8	24.7	Brucite	—	2.1
MgO	23.9	17.4	Hydromagnesite	15.3	3.6
CO_2	43.5	35.5	Dolomite	60.3	61.9
H_2O	3.1	1.6	Calcite	19.1	10.3

patches, in stringers, and in grains 1 to 3 millimeters in diameter. Further reference to this disseminated magnetite will be made in connection with the associated cellular limestone.

CELLULAR LIMESTONE

In parts of some brucitic limestone deposits, notably that at Bass Lake, granular brucite has been almost entirely leached out to depths of over 100 feet, leaving a cellular limestone. Much of the cellular rock is partially impregnated with magnetite (Table 3).

The similar shape, size, and distribution of brucite in the limestone, of cavities in cellular limestone, and of magnetite grains in iron-impregnated limestone leave little doubt that much of the magnetite either replaced brucite or was deposited in the cavities after brucite had been removed. Figures 5 and 6 of Plate 2 show the shape of cavities and magnetite grains, as well as the cloudy haloes or reaction rims which are similar to those observed around some granular brucite in dolomite. (Cf. Pl. 1, fig. 3).

Normally the weathering of brucite does not extend more than a quarter to half an inch below an outcrop surface. Therefore complete removal of brucite to great depths cannot be attributed to weathering processes operative since the period of Pleistocene glaciation. The brucite may have been removed by preglacial weathering, but the association of disseminated magnetite with cellular limestone suggest the activity of magmatic solutions during or after the removal of brucite. Therefore it seems logical to conclude that magmatic solutions probably effected both the removal of brucite and the deposition of magnetite.

GENESIS OF BRUCITIC LIMESTONE

A. F. Rogers (1918), discussing an occurrence at Riverside, California, advanced the classical theory of origin of brucite—that periclase formed from dissociation of

dolomite under conditions of thermal metamorphism and that the periclase subsequently was hydrated to brucite. He reported small remnants of periclase within brucite granules, whose internal "onion-skin" texture is very similar to textures observed in granular brucite from Wakefield and Rutherglen. Goudge (1940) and Ambrose (1943) suggested a similar origin for brucite at Wakefield, Quebec.

In trying to arrive at the most reasonable explanation which fits the evidence offered by the occurrences of brucitic limestone in the Rutherglen District one must consider the probable composition of the carbonate rock before brucitization and the source of the magnesia, as well as the agents and processes by which the several modifications of brucite were formed. It is not proposed to consider here the problems of dolomitization. The Rutherglen deposits of brucitic limestone have a molecular ratio of MgO to CaO higher than that of pure dolomite. Therefore the composition of the brucite deposits cannot be explained as due solely to dissociation and hydration of dolomite. It is necessary to explain the additional magnesia. There would seem to be three possible explanations for this. Goudge (1939, p. 9) suggested two of them—either the source rocks consisted of magnestic dolomite, or there was some dolomitization subsequent to the formation of brucite. A third possibility is that some of the MgO in brucite was contributed by the intrusive or, more probably, by the dissociation of dolomite at contacts. It is difficult to prove or disprove the first two possibilities; magnesite has not been identifield in the crystalline limestone from Rutherglen, although recasts of some chemical analyses require small amounts of that mineral. No evidence of post-brucite dolomitization was found.

There is some evidence to support the idea of concentration of magnesia by dissociation of dolomite and selective transfer of the products of dissociation into the overlying roof pendants. Large amounts of dolomite must have been dissociated at contacts, since the present carbonate masses are only remnants of a once continuous series. The activity of magnesia-bearing gases or solutions is attested by the occurrence of vein brucite and by the abundant stringers and lenses of serpentine in the carbonate rocks. Replacement of carbonates by brucite is strongly suggested by the shape of brucite granules, particularly those with angular outlines conformable with cleavage directions of the enclosing dolomite. Further evidence of replacement is offered by projecting tongues of brucite which in some cases extend from brucite granules into the surrounding carbonates.

On the basis of the above evidence it is suggested that vein brucite and the abundant irregular and angular grains were deposited directly by magnesia-bearing gases or solutions.

The platy or foliated form of brucite probably was formed by the dissociation and hydration of dolomite to an intergrowth of calcite and brucite. Again the textural relations, particularly the exclusive occurrence of foliated brucite in calcite and its termination against dolomite, cannot reasonably be explained otherwise.

The rounded brucite granules which show a scaly concentric internal texture may be secondary after periclase, but there is no supporting evidence other than the textural similarity of the brucite granules to those described by A. F. Rogers (1929) and by Hunt and Faust (1937) as containing periclase cores.

The writer believes the probable sequence of events which effected concentration of magnesia and formation of brucite and associated metasomatic and metamorphic minerals in the original dolomitic limestone was as follows:

(1) If periclase formed, it would be at an early stage of dry thermal metamorphism. Spinel and forsterite probably were formed early, spinel where there were local concentrations of alumina, forsterite where there were concentrations of silica in the limestone.

(2) In a second stage superheated steam from the crystallizing magma reacted with dolomite to form the intergrowth of calcite and foliated brucite. The steam or subsequent solutions, charged with magnesia derived from the dissociation of dolomite at contacts, deposited brucite in veins and in irregular replacement granules and at the same time partially altered spinel and forsterite to serpentine.

(3) In a final stage, after the temperature at contacts had fallen below the dissociation point of dolomite, dilute magmatic solutions, no longer heavily charged with magnesia, penetrated some sections of brucitic limestone, partially removed brucite and left the cellular limestone. The same late-stage solutions probably deposited magnetite in the cavities.

In summary, it seems likely that the concentration of magnesia and the genesis of the brucitic limestone must be attributed to successive stages of activity of the adjacent intrusive and its emanations, although the bulk of the magnesia probably came from the carbonate series itself.

With regard to the conditions under which dolomite may undergo dissociation and accompanying hydration to produce calcite and brucite, the writer has begun an investigation of the action of superheated steam on dolomite, first repeating under controlled conditions some early experiments of Lemberg (1874, p. 230). It is hoped that the investigation may also yield some information regarding the transfer of magnesia.

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EXPLANATION OF PLATES 1 AND 2

PLATE 1.—PHOTOMICROGRAPHS

Figure

1. —Stained brucitic limestone showing shape of brucite granules and distribution of brucite (dark) in matrix of calcite (slate gray) and dolomite (white). Some foliated brucite (pale gray) can be seen within calcite. Actual colors are: granular brucite blue, calcite violet, dolomite white. × 4.5
2. —Brucite granule (low relief) in dolomite (high relief), showing angular outline of brucite related to cleavage directions of the enclosing dolomite. Also shown is the clouded zone in dolomite surrounding brucite. × 25
3. —Brucite granule in carbonate matrix, showing angular outline of brucite in contact with dolomite (on the right), contrasted with irregular rounded outline of the same granule in contact with calcite (on the left). The calcite encloses some foliated brucite. Shown also is the clouded zone in dolomite around brucite. × 60

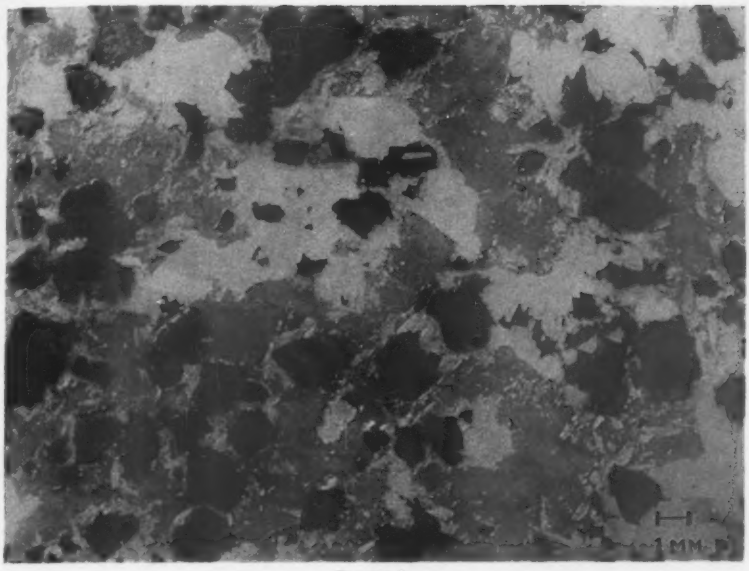

FIGURE 1

FIGURE 2

1 MM.

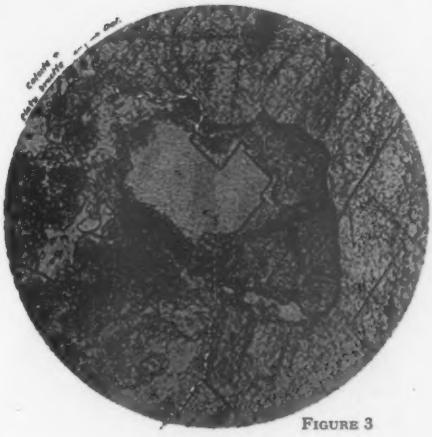

FIGURE 3

1 MM.

PHOTOMICROGRAPHS

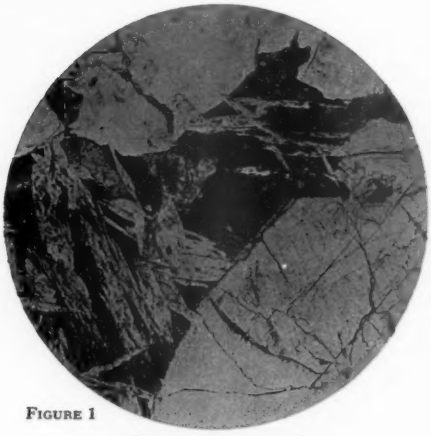

FIGURE 1

1 MM.

FIGURE 2

1 MM.

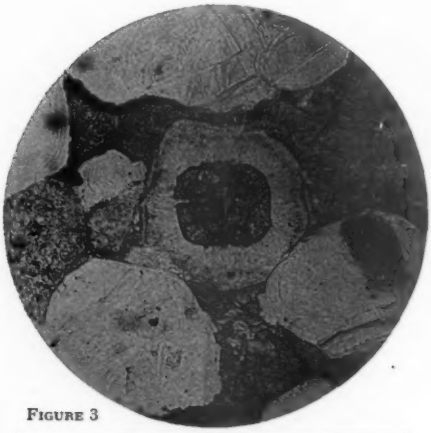

FIGURE 3

1 MM.

FIGURE 4

1 MM.

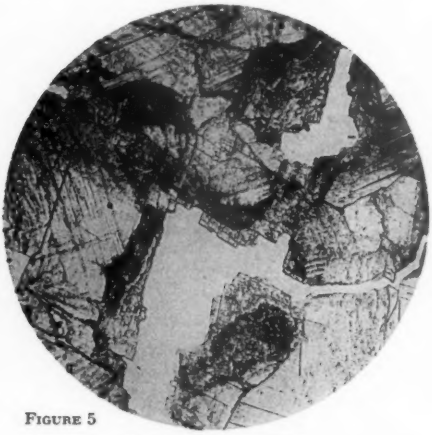

FIGURE 5

1 MM.

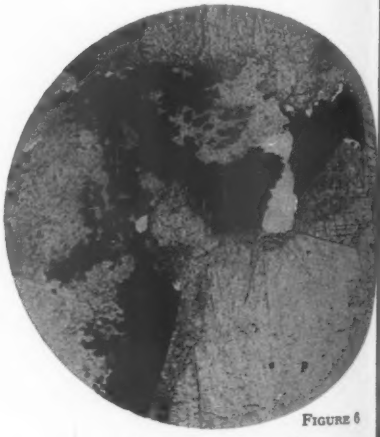

FIGURE 6

1 MM.

PHOTOMICROGRAPHS

PLATE 2.—PHOTOMICROGRAPHS

Figure

1.—Foliated brucite (wedge-shaped crystals) in calcite (dark-stained) and terminated against dolomite (clear, showing rhombohedral cleavage). In the upper part of the photomicrograph are shown several granules of brucite (low relief). × 25

2.—Remnants of magnesia spinel (high relief) enclosed in radiated serpentine. × 60

3.—Two types of serpentine: type 1 (low relief, reticulated), which is derived from forsterite, and type 2 (low relief, radiated), which is derived from spinel (high relief, quadratic). The matrix is calcite and dolomite. × 60

4.—Same as Figure 3 but with crossed nicols. × 60

5.—Angular cavities in cellular crystalline dolomite. The angular outline and the clouded peripheral zone are comparable to those of granular brucite (Pl. 1, figs. 2, 3) amd to those of magnetite in dolomite (Fig. 6 of this plate). × 25

6.—Magnetite in crystalline limestone, showing contrast between straight regular contact with dolomite (on the right) and irregular contact with calcite (on the left and above). Also shown is the clouded zone in dolomite adjacent to magnetite (Cf. Pl. 1, figs. 2, 3 and Fig. 5 of this plate.)

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